

## **General Disclaimer**

### **One or more of the Following Statements may affect this Document**

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

NASA TECHNICAL  
MEMORANDUM

NASA TM X- 64987

(NASA-TM-X-64987) ATMOSPHERIC TRANSMISSION  
OF CO<sub>2</sub> LASER RADIATION WITH APPLICATION TO  
LASER DOPPLER SYSTEMS (NASA) 52 p HC \$4.50  
CSCL 20

N76-18436

CSCI 20E

Unclassified

G3/36 18518

# ATMOSPHERIC TRANSMISSION OF CO<sub>2</sub> LASER RADIATION WITH APPLICATION TO LASER DOPPLER SYSTEMS

By S. S. R. Murty  
Electronics and Control Laboratory

November 28, 1975

NASA



*George C. Marshall Space Flight Center  
Marshall Space Flight Center, Alabama*

## TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. NASA TM X- 64987	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.	
4. TITLE AND SUBTITLE Atmospheric Transmission of CO <sub>2</sub> Laser Radiation with Application to Laser Doppler Systems		5. REPORT DATE November 28, 1975	
7. AUTHOR(S) S. S. R. Murty	6. PERFORMING ORGANIZATION CODE		
9. PERFORMING ORGANIZATION NAME AND ADDRESS George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812		8. PERFORMING ORGANIZATION REPORT #	
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, D.C. 20546		10. WORK UNIT NO.	
		11. CONTRACT OR GRANT NO.	
		13. TYPE OF REPORT & PERIOD COVERED Technical Memorandum	
14. SPONSORING AGENCY CODE			
15. SUPPLEMENTARY NOTES Prepared by Electronics and Control Laboratory, Science and Engineering			
16. ABSTRACT <p>The molecular absorption coefficients of carbon dioxide, water vapor, and nitrous oxide are calculated at the P16, P18, P20, P22, and P24 lines of the CO<sub>2</sub> laser for temperatures from 200 to 300 K and for pressures from 100 to 1100 mb. The temperature variation of the continuum absorption coefficient of water vapor is taken into account semi-empirically from Burch's data. The total absorption coefficient from the present calculations falls within ±20 percent of the results of McClatchey and Selby. The transmission loss which the MSFC CO<sub>2</sub> pulsed laser Doppler system experiences has been calculated for the January 1973 flight-test conditions for the five P-lines. The total transmission loss is approximately 7 percent higher at the P16 line and 10 percent lower at the P24 line compared to the P20 line. Comparison of the CO<sub>2</sub> laser with HF and DF laser transmission reveals that P<sub>2</sub>(8) line at 3.8 μm of the DF laser is much better from the transmission point of view for altitudes below 10 km.</p>			
17. KEY WORDS		18. DISTRIBUTION STATEMENT Unclassified-Unlimited <i>Refined 11/28/75</i>	
19. SECURITY CLASSIF. (of this report) Unclassified	20. SECURITY CLASSIF. (of this page) Unclassified	21. NO. OF PAGES 53	22. PRICE NTIS

## ACKNOWLEDGMENTS

The author is grateful to his Scientific Advisor, Mr. R. M. Huffaker, for all the discussions and for his invaluable interest and assistance. The author acknowledges gratefully the discussions with Dr. J. L. Randall (NASA/MSFC), Dr. T. R. Lawrence (Lockheed/Huntsville, AL) and Dr. Alex Thomson (Physical Dynamics, Berkeley, CA).

## TABLE OF CONTENTS

	Page
I. INTRODUCTION.....	1
II. CALCULATION OF THE ABSORPTION COEFFICIENT .....	3
III. ABSORPTION BY CARBON DIOXIDE .....	4
IV. ABSORPTION BY WATER VAPOR.....	5
V. ABSORPTION BY NITROUS OXIDE .....	7
VI. COMPARISON WITH AFCRL CALCULATIONS.....	8
VII. APPLICATION TO PULSED LASER DOPPLER SYSTEM .....	8
VIII. LASERS WITH LOW TRANSMISSION LOSS .....	13
IX. CONCLUSIONS.....	14
REFERENCES .....	43

## LIST OF ILLUSTRATIONS

Figure	Title	Page
1.	Near-infrared solar spectrum, spectra of various atmospheric gases and operating frequencies of HF, DF, and CO <sub>2</sub> lasers . . . . .	15
2.	Variation of two-way transmission loss with altitude for P and R-lines of CO <sub>2</sub> laser in AFCRL Midlatitude Summer Hazy Atmosphere . . . . .	16
3.	Absorption coefficient of carbon dioxide at T = 300 K . . . . .	17
4.	Absorption coefficient of carbon dioxide at T = 200 K . . . . .	18
5.	Absorption coefficient of carbon dioxide at $\nu = 947.738 \text{ cm}^{-1}$ . . . . .	19
6.	Absorption coefficient of carbon dioxide at $\nu = 945.976 \text{ cm}^{-1}$ . . . . .	20
7.	Absorption coefficient of carbon dioxide at $\nu = 944.190 \text{ cm}^{-1}$ . . . . .	21
8.	Absorption coefficient of carbon dioxide at $\nu = 942.38 \text{ cm}^{-1}$ . . . . .	22
9.	Absorption coefficient of carbon dioxide at $\nu = 940.544 \text{ cm}^{-1}$ . . . . .	23
10.	Continuum absorption coefficient of H <sub>2</sub> O at different temperatures . . . . .	24
11.	Absorption coefficient of water vapor continuum for 1 PR-CM at 10.6 $\mu\text{m}$ . . . . .	25
12.	Absorption coefficient of 1 PR-CM of water vapor lines at T = 300 K . . . . .	26
13.	Absorption coefficient of 1 PR-CM of water vapor lines at T = 200 K . . . . .	27

## LIST OF ILLUSTRATIONS (Concluded)

Figure	Title	Page
14.	Absorption coefficient of water vapor lines at $\nu = 940.544$ $\text{cm}^{-1}$ for 1 PR-CM .....	28
15.	Absorption coefficient of water vapor lines at $\nu = 942.38$ $\text{cm}^{-1}$ for 1 PR-CM .....	29
16.	Absorption coefficient of water vapor lines at $\nu = 944.19$ $\text{cm}^{-1}$ for 1 PR-CM .....	30
17.	Absorption coefficient of water vapor lines at $\nu = 945.976$ $\text{cm}^{-1}$ for 1 PR-CM .....	31
18.	Absorption coefficient of water vapor lines at $\nu = 947.738$ $\text{cm}^{-1}$ for 1 PR-CM .....	32
19.	Absorption coefficient of nitrous oxide lines at $T = 300 \text{ K}$ ...	33
20.	Absorption coefficient of nitrous oxide at $T = 200 \text{ K}$ .....	34
21.	Absorption coefficient of nitrous oxide lines at $\nu = 940.544$ $\text{cm}^{-1}$ .....	35
22.	Absorption coefficient of nitrous oxide at $\nu = 942.38 \text{ cm}^{-1}$ ...	36
23.	Absorption coefficient of nitrous oxide lines at $\nu = 944.19$ $\text{cm}^{-1}$ .....	37
24.	Absorption coefficient of nitrous oxide lines at $\nu = 945.976$ $\text{cm}^{-1}$ .....	38
25.	Absorption coefficient of nitrous oxide lines at $\nu = 947.738$ $\text{cm}^{-1}$ .....	39
26.	Total transmission loss at the P lines for flight B8, run 18, 1/19/1973 at Edwards AFB .....	40
27.	Comparison of measured and theoretical S/N values .....	41
28.	Performance of CO <sub>2</sub> , HF and DF laser Doppler systems against ground target at 15° inclination in AFCRL Midlatitude Summer Atmosphere .....	42

## LIST OF TABLES

Table	Title	Page
1.	Transmission Losses .....	2
2.	Comparison with the Results of McClatchey and Selby.....	8
3.	Calculation of Absorption Coefficient for Flight B8, Run 18, 1/19/1973, Edwards AFB .....	11
4.	Molecular Absorption Coefficient of P Lines and Aerosol Attenuation per km .....	12
5.	Two-Way Horizontal Transmission Loss for Infrared Lasers Over 40 km Range .....	13

# ATMOSPHERIC TRANSMISSION OF CO<sub>2</sub> LASER RADIATION WITH APPLICATION TO LASER DOPPLER SYSTEMS

## I. INTRODUCTION

Marshall Space Flight Center (MSFC) has been developing laser Doppler systems for remote measurement of wind speed and turbulence for over a decade. Some of these systems designed to operate over long atmospheric paths are affected by the attenuation due to the atmospheric gases, particulate matter, and turbulence. The transmission losses due to the molecular gases and aerosols are considered in this report. The effects of atmospheric turbulence on the performance of the laser Doppler system will be considered in a later publication.

The transmission losses are characterized as linear or nonlinear to distinguish between laser power-independent and power-dependent processes. We consider the linear transmission losses. The infrared 10.6  $\mu\text{m}$  spectral region lies in one of the atmospheric transmission windows and is the wavelength at which CO<sub>2</sub> laser operates efficiently. An atmospheric window is a spectral region over which the absorption by the permanent gases is relatively weak and is usually chosen for atmospheric propagation to keep the absorption losses to a minimum.

The atmospheric windows in the infrared lie between the strong bands of carbon dioxide and water vapor which are the two major absorbing gases in the infrared. Figure 1 shows a low resolution absorption spectrum of solar radiation at ground level from 1 to 15  $\mu\text{m}$  [1] together with the spectra of various atmospheric gases from the laboratory measurements for comparison and the operating wavelength region of HF\*, DF\*\*, and CO<sub>2</sub> lasers. Except for ozone and water vapor, the other absorbing gases are generally uniformly mixed.

None of the windows are completely transparent as a result of molecular absorption and scattering by particulate matter. The CO<sub>2</sub> laser lines have a typical line width of  $2 \times 10^{-5} \mu\text{m}$  or 60 mHz while the absorption lines of atmospheric gases are several orders of magnitude wider. McClatchey and Selby [2]

\* Hydrogen Fluoride

\*\* Deuterium Fluoride

have calculated the atmospheric transmission in the  $10.6 \mu\text{m}$  region for a set of standard atmospheric conditions. Their results are shown as two-way losses in dB for the AFCRL\* Mid-Latitude Summer Hazy Atmosphere for some P-lines and R-lines in Figure 2. The transmission losses for several lines at 3.5 km altitude for a 10 km horizontal path are shown in Table 1.

TABLE 1. TRANSMISSION LOSSES

Laser Line	Loss (dB)	Laser Line	Loss (dB)
P40*	2.15	P4	3.58
P32	5	R0*	2.2
P20	7.85	R12	6.8
P18	10.4	R22	6.3
P14	9.23	R30	4.6
P6	4.64		

\*P40 and R0 lines have the least transmission loss.

The atmospheric conditions are variable and deviations from the standard AFCRL models can result in large errors in the absorption coefficient. The purpose of this report is to provide the absorption coefficient of each of the molecules relevant for CO<sub>2</sub> laser radiation for various pressures and temperatures of interest in the lower atmosphere. The transmission may then be calculated at the prevailing atmospheric conditions.

The pulsed laser Doppler system developed by MSFC for the detection and measurement of atmospheric turbulence uses a CO<sub>2</sub> laser beam propagating in the atmosphere over several kilometers. The atmospheric data obtained during the flight tests at Edwards AFB are used to calculate the transmission loss which the system experiences and are compared with the measured signal-to-noise (S/N) ratio. The transmission loss is found to be significant and serves to explain a large part of the losses leading to the  $1/R^3$  falloff of the measured S/N values instead of the theoretical  $1/R^2$  falloff where R is the range. The transmission loss may be reduced by operating at a different infrared wavelength. The P<sub>2</sub>(8) line at  $3.8 \mu\text{m}$  of the DF laser experiences a transmission loss which is much less than that of the CO<sub>2</sub> laser.

\*Air Force Cambridge Research Laboratories

## II. CALCULATION OF THE ABSORPTION COEFFICIENT

The molecules active in the  $10 \mu\text{m}$  region of the infrared are methane,  $\text{CH}_4$ ; ethylene,  $\text{C}_2\text{H}_4$ ; nitrous oxide,  $\text{N}_2\text{O}$ ; ammonia,  $\text{NH}_3$ ; Ozone,  $\text{O}_3$ ; nitric acid,  $\text{HNO}_3$ ; carbon dioxide,  $\text{CO}_2$ ; and water,  $\text{H}_2\text{O}$ . Excluding water vapor; nitrogen, oxygen, argon, and carbon dioxide are the four major constituents of the atmospheric gases. The remaining gases constitute less than 0.004 percent of the total by volume. It is assumed that all of the gases except water vapor and ozone are uniformly mixed by volume in the atmosphere.

The absorption coefficient for each line as a function of frequency is assumed to be described by the Lorentz relation

$$k(\nu) = \frac{S \alpha}{\pi[(\nu - \nu_0)^2 + \alpha^2]} \quad (1)$$

where  $\nu_0$  ( $\text{cm}^{-1}$ ) is the resonant frequency,  $S$  ( $\text{cm}^{-1}/\text{molecules cm}^{-2}$ ) is the line intensity per absorbing molecule, and  $\alpha$  ( $\text{cm}^{-1}$ ) is the Lorentz line width parameter. The validity of equation (1) to describe the correct line shape in the wings has been in doubt specially for carbon dioxide and water vapor. The Lorentz shape overpredicts the wings for carbon dioxide while underestimating for water vapor.

The line intensity is independent of pressure but is dependent on temperature and is given by

$$S(T) = S(T_s) \frac{Q_v(T_s)}{Q_v(T)} \frac{Q_r(T_s)}{Q_r(T)} \exp \left[ \frac{1.439 E''(T - T_s)}{T T_s} \right]$$

where  $E''$  ( $\text{cm}^{-1}$ ) is the energy of the lower state of the transition,  $Q_v$  and  $Q_r$  are the vibrational and rotational partition functions, respectively, and  $T_s$  is standard temperature, 296 K.

The half-width of the line depends on the pressure and temperature as follows:

$$\sigma = \sigma_0 \frac{p}{p_0} \left( \frac{T_0}{T} \right)^n$$

where  $n$  is usually assumed equal to  $1/2$ .  $n = 0.62$ , suggested by Benedict and Kaplan [3], is used for water vapor. Measurements by Ely and McCubbin [4] at high temperatures and by Tubbs and Williams [5] at temperatures lower than the room value suggest that the half-width variation of carbon dioxide is closer to  $n = 1$  than  $n = 1/2$ . The exact dependence is uncertain and appears to depend on the rotational quantum number of the line. In the absence of more accurate information, we use the usual  $n = 1/2$  in this work for carbon dioxide.

The four absorption line parameters  $\nu_0$ ,  $S$ ,  $\alpha$ , and  $E'$  have been listed for the seven molecules  $H_2O$ ,  $CO_2$ ,  $O_3$ ,  $N_2O$ ,  $CO$ ,  $CH_4$ , and  $O_2$  by McClatchy et al [6] from the existing information and these are used here for the line-by-line calculation of the absorption coefficient at the laser line frequencies.

The atmospheric carbon dioxide and water vapor are the major attenuators at the  $CO_2$  laser line frequencies. The concentrations of the trace gases and pollutants are too low to have any significant effect. A simple estimate may be made as follows. At the line center, the absorption coefficient is  $K = S/\pi c$  per molecule. For a concentration of 1 ppm, the number of molecules in 1 km path is approximately  $10^{18}$ . For  $S = 10^{-23}$  and  $\pi c = 0.1$ , one obtains  $K = 10^{-1}$  c/km where  $c$  is the number of ppm. Most of the trace gases have a concentration  $c$  of unity or less. For instance, ozone has a concentration of approximately 0.02 ppm at sea level and 0.2 ppm at 25 km.  $N_2O$  has a concentration of 0.28 ppm. The effect of the trace gases is thus very small compared to  $CO_2$  and  $H_2O$ . Among the trace gases,  $N_2O$  has several lines in the  $10 \mu m$  region and its effect has been calculated to give an idea of its contribution to the absorption. At altitudes higher than 12 km, ozone absorption may become important specially at the R-lines of  $CO_2$  laser. In addition to the molecular absorption, scattering and absorption due to the aerosols must be included in obtaining the total absorption coefficient.

### III. ABSORPTION BY CARBON DIOXIDE

The absorption coefficient at the center of P20 laser line by the atmospheric carbon dioxide has been calculated by Yin and Long [7] and they gave polynomial fits to the absorption coefficient as a function of altitude for two

model atmospheres. The wings of neighboring lines also contribute to the absorption at any laser line frequency. In this work, lines within  $\pm 20 \text{ cm}^{-1}$  are assumed to contribute to the absorption. A concentration of 330 ppm of CO<sub>2</sub> in the atmosphere is assumed. The effect of including the wings of the neighboring lines is approximately an increase of 3 to 5 percent at the P20 line. Since the CO<sub>2</sub> laser operates efficiently around the P20 line, the absorption coefficients for P16, P18, P20, P22, and P24 lines are calculated for temperatures and pressures of interest in the lower atmosphere. The effect of temperature on the absorption coefficient may be seen from Figures 3 and 4. The absorption coefficients for P16, P18, and P20 lines are approximately the same at 300 K and they separate out at 200 K. The absorption coefficients are almost independent of pressure and the slight pressure dependence comes from the line wings as the absorption at the line center is independent of pressure. Figures 5 through 9 give the absorption coefficient at the individual laser lines for pressures from 100 to 1100 mb and temperatures from 200 K to 300 K.

#### IV. ABSORPTION BY WATER VAPOR

Many weak absorption lines of water vapor occur in the 10  $\mu\text{m}$  region. On the basis of these lines, there should be an almost complete transparency in this region for reasonable atmospheric water vapor content. The measurements of heat radiation of the sky gave higher values of total radiation than would be expected due to the rotational lines of water vapor. To explain the observed higher emissions, the existence of a water vapor continuum in the 8 to 14  $\mu\text{m}$  atmospheric window and beyond due to the wings of strong lines located in the bands on either side of the window was first suggested by Elsasser [8] in 1938. The existence of continuum absorption by water vapor has been well established now due to the several experimental observations on solar spectrum and in the laboratory [9-14]. However, the theory based on the usual line shapes has not been successful in explaining the experimental observations. Thus the calculations have to be based on the available experimental results.

McCoy, Rensch, and Long [14] measured the absorption of the water vapor continuum and suggested the empirical equation,

$$K = 4.32 \times 10^{-6} p(P + 193 p) \text{ km}^{-1}, \quad (2)$$

where  $p$  is the partial pressure of water vapor and  $P$  is the total pressure, both in Torr. This relation has been widely used to estimate the water vapor absorption. Equation (2) takes care of the pressure dependence and is valid at

the room temperature. The continuum absorption has been observed to decrease with increasing temperature and vice versa.

Burch [15] measured the continuum absorption coefficient for pure water vapor at three temperatures and his results are shown in Figure 10. The points marked are the revised values and are 10 to 15 percent less than the solid curves obtained in the earlier measurements [16]. The rapid decrease in the absorption coefficient with increasing temperature is a prominent feature of these results. The association of water molecules due to hydrogen bonding (dimerization) proposed by Varanasi, Chow, and Penner [17] predicts the trend of observed temperature dependence of the continuum absorption coefficient.

For atmospheric transmission studies, we are interested in temperatures less than 296 K. Since no data are available at low temperatures, an empirical extrapolation suggested by Burch is used in this work:

$$C_s^\circ(T) = C_s^\circ(296) \left(\frac{296}{T}\right)^\tau \quad (3)$$

where  $C_s^\circ$  is the absorption coefficient, molecule<sup>-1</sup> cm<sup>2</sup> atm<sup>-1</sup>, and  $\tau$  is to be determined from the experimental values. At 10.6  $\mu\text{m}$ , we find that  $\tau = 5.300$  for  $T = 358$  K and  $\tau = 5.25$  for  $T = 392$  K.  $\tau$  appears to decrease slightly with temperature. These  $\tau$  values are for temperatures above room temperature; no laboratory measurements are available for temperatures below room temperature. One value of the absorption coefficient at  $T = 283$  K is 10 g<sup>-1</sup> cm<sup>2</sup> atm<sup>-1</sup> from Figure 8 of Bignell's [13] paper from the solar spectrum observations. The magnitude of the error is unknown here. This value corresponds to  $\tau = 5.1$  at  $T = 283$  K. Thus the value of  $\tau$  appears to remain close to 5 even below  $T = 296$  K. We assume  $\tau = 5.25$  in this work.

There is also the effect of foreign gas broadening on the continuum absorption. The results of McCoy, Rensch, and Long give  $C_B^\circ \approx 0.005 C_s^\circ$  at room temperature. The continuum absorption coefficient is given by  $K = Cu$  where  $u$  is the absorber thickness expressed in molecules cm<sup>-2</sup> and  $C$  is given by

$$C = C_s^\circ p + C_B^\circ P \quad (4)$$

where  $p$  is the partial pressure of water vapor and  $P$  is the total pressure, both in atmospheres. The partial pressure of water vapor may be obtained from

$$p = 4.56 \times 10^{-5} w T \quad (5)$$

where  $w$  is the number of  $\text{gm-cm}^{-2}/\text{km}$  of water vapor. The water vapor is usually expressed in units of precipitable centimeters which is the same as  $\text{gm-cm}^{-2}$ . The absorber thickness  $u$  is given by

$$u = 3.34 \times 10^{22} w = \frac{7.18 \times 10^{23} p}{T} \text{ molecules/cm}^2 \quad (6)$$

The continuum absorption may be written as follows after combining equation (3) to equation (6):

$$K = \frac{1.58 \times 10^5}{T} \left( \frac{296}{T} \right)^{5.25} p(p + 0.005 P) \text{ km}^{-1} \quad (7)$$

We used  $C_s^\circ = 2.2 \times 10^{-22} \text{ molecules}^{-1} \text{ cm}^2 \text{ atm}^{-1}$  at  $10.6 \mu\text{m}$ . Equation (7) is used in this work to calculate the water vapor continuum absorption coefficient for all  $\text{CO}_2$  laser lines shown in Figure 11.

In addition to the continuum, rotational lines of water vapor absorb in the  $10.6 \mu\text{m}$  region. Line-by-line calculation is performed for lines which are within  $\pm 20 \text{ cm}^{-1}$  from the laser line. The line parameters tabulated by McClatchy et al are used in these calculations. The effects of varying the pressure and the temperature are shown in Figures 12 to 18.

## V. ABSORPTION BY NITROUS OXIDE

Nitrous oxide has several lines in the  $10 \mu\text{m}$  region. The absorption due to these lines at the laser line frequencies is obtained by a line-to-line calculation assuming that lines within  $\pm 20 \text{ cm}^{-1}$  contribute. The concentration of  $\text{N}_2\text{O}$

is assumed to be 0.28 ppm. The results are shown in Figures 19 to 25 for various pressures and temperatures. It may be seen that the absorption of  $\text{N}_2\text{O}$  is approximately two orders of magnitude less than that of  $\text{CO}_2$ .

## VI. COMPARISON WITH AFCRL CALCULATIONS

The present calculations are compared in Table 2 with those of McClatchey and Selby [2] for the AFCRL Standard Atmospheric Models at sea level. Our results have been within  $\pm 20$  percent of AFCRL numbers.

TABLE 2. COMPARISON WITH THE RESULTS OF MCCLATCHEY AND SELBY

	Tropical		Midlatitude Summer		Midlatitude Winter		Subarctic Summer	
	AFCRL	Present	AFCRL	Present	AFCRL	Present	AFCRL	Present
P16	0.5722	0.5481	0.3527	0.3728	0.07466	0.09775	0.1953	0.2274
P18	0.6346	0.4972	0.4146	0.3377	0.1223	0.0907	0.2548	0.2065
P20	0.6094	0.5051	0.3852	0.3419	0.09575	0.08964	0.2238	0.2078
P22	0.6058	0.4842	0.3867	0.3266	0.1021	0.084	0.229	0.1973
P24	0.6029	0.4796	0.3815	0.3216	0.09554	0.0795	0.2223	0.1921

## VII. APPLICATION TO PULSED LASER DOPPLER SYSTEM

Huffaker [18, 19, 20, 21] discussed the various laser Doppler systems which are being developed at NASA/MSFC. The pulsed laser Doppler system utilizes the natural particulate matter of the air for long range atmospheric applications. It consists of a coherent  $\text{CO}_2$  laser operating at  $10.6 \mu\text{m}$  and transmits 140 pps adjustable in width from 2 to  $10 \mu\text{s}$  through a modified Cassegrain telescope. A homodyne receiver collects the back scattered laser radiation which is detected by a cooled infrared detector and processed in signal processing electronics. This system was carried aboard Ames Convair 990 airplane and has been flight-tested at Edwards AFB. The atmospheric temperature, dew point, and altitude are measured along the flight path in addition to

the S/N value, particle concentrations, etc. The values obtained during the descent of the airplane against the uniform target of Rogers Dry Lake are used to calculate the transmission loss for five P lines and the effect on the S/N ratio.

The S/N ratio for the pulsed laser heterodyne system is given by [19]

$$\frac{S}{N} = \frac{E \sigma' \eta_d \eta_s \eta_a d^2}{16 h \nu \left[ R^2 + \left( \frac{\pi d^2}{4\lambda} \right)^2 \right]} \quad (8)$$

for reflection against a target filling the beam which is focused to infinity. The symbols and their values are as follows:

<u>Parameter</u>	<u>Symbol</u>	<u>Value</u>
Signal-to-Noise Power Ratio	S/N	
Laser Pulse Energy	E	12 mJ
Modified Target Cross-section	$\sigma'$	0.05 ster <sup>-1</sup>
Target Range	R	
Aperture Diameter	d	10 in.
System Efficiency	$\eta_s$	0.05
Detector Quantum Efficiency	$\eta_d$	0.25
Atmospheric Transmission	$\eta_a$	
Wavelength	$\lambda$	$1.06 \times 10^{-5}$ m
Energy per Photon	$h\nu$	$1.9 \times 10^{-20}$ J.

The atmospheric transmission loss  $\eta_a$  is calculated from

$$\eta_a = \exp \int_0^R 2 K(R) dR \quad (9)$$

The range is converted into altitude by the relation

$$H = 1.97 \text{ kft} + R \sin 7^\circ \quad (10)$$

for the flight data of January 1973.

The loss in S/N ratio due to atmospheric absorption at any range is calculated from

$$\left(\frac{S}{N}\right)_{\text{Atm. Loss}} = \frac{1.97}{8.68} \int_0^H K(H) \frac{dH}{\sin 7^\circ} \quad \text{dB} \quad (11)$$

The measured values of the static temperature ( $T_s$ ) and the dew-point temperature ( $T_d$ ) along the flight path at various altitudes for flight B8, Run 18, 1/19/1973, at Edwards AFB are given in Table 3. The individual molecular absorption coefficients corresponding to these atmospheric conditions are calculated from the data of this report and are shown in detail for the P20 line. The aerosol attenuation must also be added to obtain the total absorption coefficient. The aerosol absorption and scattering coefficients for the hazy condition are taken from Reference 2 and are shown in Table 4 together with the total molecular absorption coefficients for five P lines. The atmospheric two-way transmission loss is calculated using equation (11) and is shown in Figure 26 for the five P lines. The P22 and P24 lines have lower loss and P16 and P18 lines have higher loss than the P20 line. The magnitude of the difference is approximately 2 dB over a path of 90 kft. Thus the variation from line to line is not significant around the P20 line. The S/N ratio corrected for the transmission loss is shown in Figure 27 together with the measured values. If there were no atmospheric losses, the curve falls off as  $1/R^2$  where R is the range. The measurements indicate a fall-off nearly as  $1/R^3$ . Though the CO<sub>2</sub> laser operates in the atmospheric window, the transmission loss is significant over long paths which may explain a large part of the losses leading to  $1/R^3$  dependence of the measured S/N values. Some of the remaining losses may be of instrument origin and some due to the atmospheric turbulence.

The range of the system will improve if the large transmission loss can be reduced. One way to reduce the transmission loss is to operate at a different infrared wavelength having less atmospheric absorption. This possibility is examined in the next section.

TABLE 3. CALCULATION OF ABSORPTION COEFFICIENT FOR FLIGHT B8,  
RUN 18, 1/19/1973, EDWARDS AFB

H (kft)	T <sub>S</sub> °C	T <sub>O</sub> °C	K <sub>CO<sub>2</sub></sub> <sup>P20</sup>	K <sub>H<sub>2</sub>O</sub> <sup>P20</sup> Continuum	K <sub>H<sub>2</sub>O</sub> <sup>P20</sup> Lines	K <sub>N<sub>2</sub>O</sub> <sup>P20</sup>	K <sub>Total</sub> km <sup>-1</sup>
2.39	-0.6	-7.9	0.05187	0.02773	0.000983	$5 \times 10^{-5}$	0.08063
3.00	-3.6	-9.4	0.04821	0.02633	0.000818	$3.9 \times 10^{-5}$	0.0754
4.00	-8.6	-9.9	0.0424	0.0309	$7.1 \times 10^{-4}$	$3.5 \times 10^{-5}$	0.07405
5.03	-10.5	-11.1	0.0404	0.0291	$6.08 \times 10^{-4}$	$3.3 \times 10^{-5}$	0.07014
5.98	-9.9	-13.8	0.04105	0.02016	$4.75 \times 10^{-4}$	$2.9 \times 10^{-5}$	0.0617
6.98	-12.3	-15.3	0.03852	0.01877	$3.95 \times 10^{-4}$	$2.6 \times 10^{-5}$	0.05771
8.00	-13.5	-16.6	0.03729	0.0168	$3.37 \times 10^{-4}$	$2.4 \times 10^{-5}$	0.05445
8.99	-15.0	-19.0	0.03579	0.01346	$2.61 \times 10^{-4}$	$2.1 \times 10^{-5}$	0.04953
10.00	-16.4	-20.8	0.03444	0.0115	$2.13 \times 10^{-4}$	$1.9 \times 10^{-5}$	0.04617
11.03	-17.3	-25.9	0.03358	0.0068	$1.29 \times 10^{-4}$	$1.8 \times 10^{-5}$	0.04053
12.02	-18.5	-27.4	0.03246	0.00568	$1.07 \times 10^{-4}$	$1.6 \times 10^{-5}$	0.03826
12.96	-19.5	-34.2	0.03156	0.00267	$5 \times 10^{-5}$	$1.5 \times 10^{-5}$	0.0343
14.00	-19.8	-45.0	0.03128	0.00075	$2 \times 10^{-5}$	$1.3 \times 10^{-5}$	0.03205
14.99	-20.7	-42.3	0.03048	0.001044	$2 \times 10^{-5}$	$1.2 \times 10^{-5}$	0.03156
16.01	-21.3	-40.6	0.02997	0.00127	$2.4 \times 10^{-5}$	$9.5 \times 10^{-6}$	0.03127

TABLE 4. MOLECULAR ABSORPTION COEFFICIENT OF P LINES AND  
AEROSOL ATTENUATION PER KM

H (kft)	K (P16)	K (P18)	K (P20)	K (P22)	K (P24)	$K_a + \sigma_a$ (aerosol)
2.39	0.08803	0.08171	0.08063	0.07512	0.07062	0.0248
3.00	0.08227	0.07658	0.0754	0.07032	0.06603	0.02075
4.00	0.08081	0.07542	0.07405	0.06963	0.06572	0.0153
5.03	0.07634	0.07143	0.07014	0.06585	0.06207	0.0114
5.98	0.06717	0.06303	0.0617	0.05747	0.05363	0.0085
6.98	0.06278	0.05903	0.05771	0.05374	0.05007	0.0057
8.00	0.05894	0.05578	0.05445	0.05062	0.04703	0.0036
8.99	0.05386	0.05087	0.04953	0.04588	0.04142	0.0026
10.00	0.05024	0.04751	0.04617	0.04267	0.0393	0.002
11.03	0.04378	0.04157	0.04053	0.03686	0.03352	0.0017
12.02	0.04167	0.0396	0.03826	0.035	0.03175	0.0013
12.96	0.03736	0.03563	0.0343	0.03125	0.02796	0.001
14.00	0.03487	0.03339	0.03205	0.029	0.02579	0.00072
14.99	0.03438	0.03288	0.03156	0.02854	0.02542	0.00053
16.01	0.03409	0.03258	0.03127	0.02829	0.02521	0.00039

## VIII. LASERS WITH LOW TRANSMISSION LOSS

Infrared transmission of HF and DF laser radiation has been calculated by Wang [23]. Spencer, Denault, and Takimoto [24] have given experimental results for several DF laser lines. We will now use this information to calculate the transmission loss for the laser Doppler system using HF and DF laser lines and compare with the CO<sub>2</sub> laser system.

The performances of CO<sub>2</sub>, HF, and DF laser Doppler systems looking down at a ground target from 5 km altitude at an inclination of 15° in AFCRL Midlatitude Summer Atmosphere are shown in Figure 28. The curves without atmospheric effects are calculated for the same values of the parameters assuming that the backscatter coefficient varies as  $1/\lambda^2$  [25]. The CO<sub>2</sub> laser experiences a loss which is 16 dB higher than that for DF laser for a slant range of 20 km.

The two-way transmission losses for a horizontal transmission over a range of 40 km at altitudes of 5 km and 10 km are given in Table 5.

TABLE 5. TWO-WAY HORIZONTAL TRANSMISSION LOSS FOR INFRARED LASERS OVER 40 km RANGE

Laser, Line and Wavelength	Loss in db	
	H = 5 km	H = 10 km
CO <sub>2</sub> , P20, 10.6 μm	19	7
HF, P <sub>2</sub> (8), 2.91 μm	4	0.6
DF, P <sub>2</sub> (8), 3.8 μm	1	0.45
CO, P <sub>6</sub> (5), 5.07 μm	3.5	0.45

The DF laser has the least loss. As the altitude increases, the magnitude of the loss reduces. At 10 km altitude, HF, DF, and CO lasers have approximately the same loss. Figure 29 gives the two-way loss as a function of altitude for these lasers in AFCRL mid-latitude summer atmosphere using data from Reference 23. DF laser is much better than the CO<sub>2</sub> laser for transmission through the atmosphere. But due to the longer wavelength, the CO<sub>2</sub> laser system has a larger coherence diameter than the DF laser system which may be an important consideration for an operating system.

## IX. CONCLUSIONS

The atmospheric transmission loss has been calculated for five P lines (P16, P18, P20, P22, and P24) of the CO<sub>2</sub> laser using the January 1973 flight test conditions. It is found that the transmission loss is approximately 7 percent higher for P16 lines and 10 percent lower for P24 line compared to the P20 line. Thus the variation of the transmission loss is not very significant around the P20 line which is the usual range of efficient operation of the CO<sub>2</sub> laser. The P40 line or R0 line have better transmission but it may not be possible to operate on these lines.

Comparison with other infrared lasers reveals that DF laser operating at 3.8  $\mu\text{m}$  on P<sub>2</sub>(8) line has the least transmission loss and that the CO<sub>2</sub> laser has higher loss at all altitudes. However for altitudes higher than 10 km, the magnitude of the loss is small, and no significant advantage appears to be gained in choosing one laser or the other.

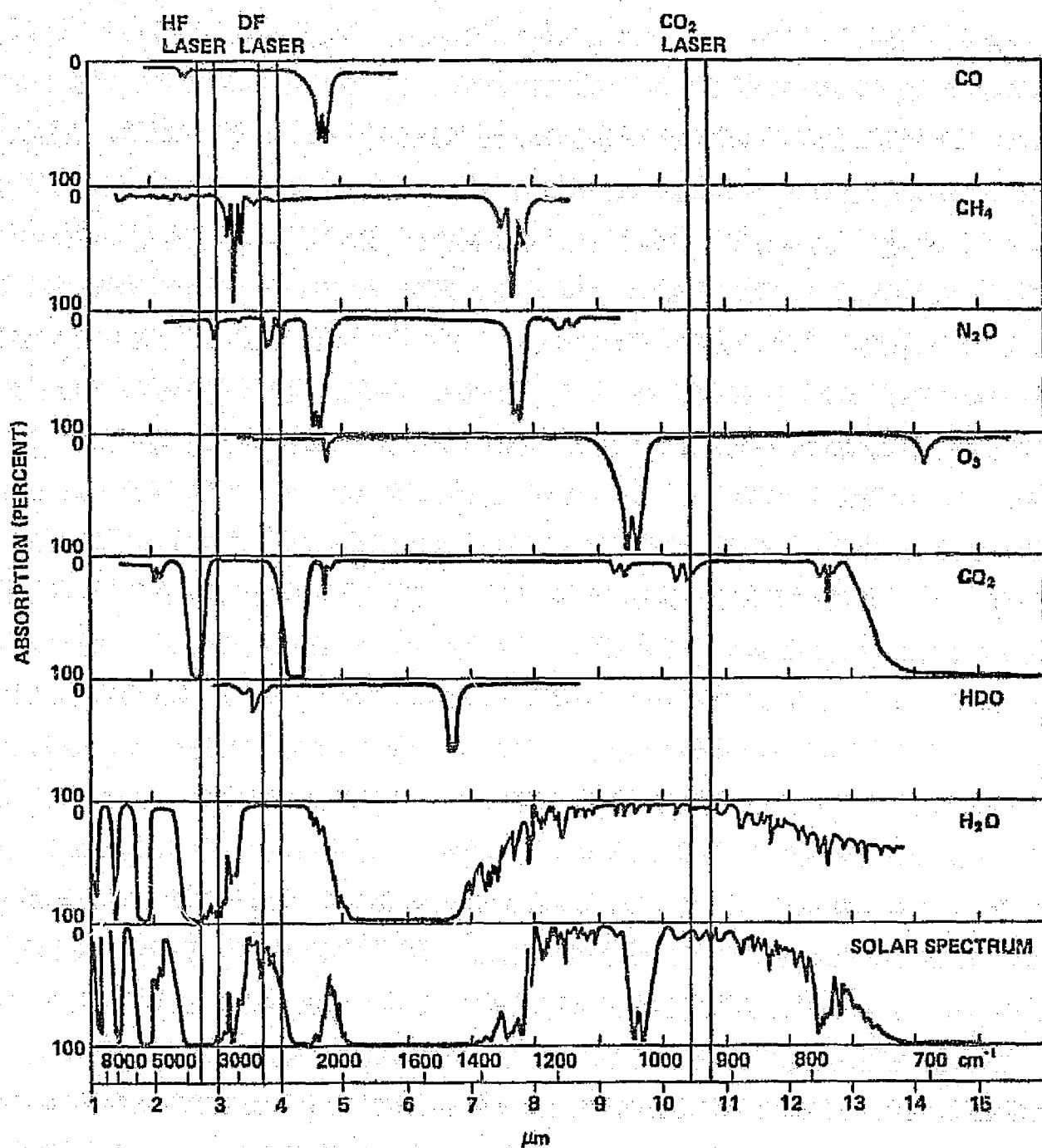


Figure 1. Near-infrared solar spectrum, spectra of various atmospheric gases and operating frequencies of HF, DF, and CO<sub>2</sub> lasers.

REPRODUCIBILITY OF THE  
ORIGINAL PAGE IS POOR

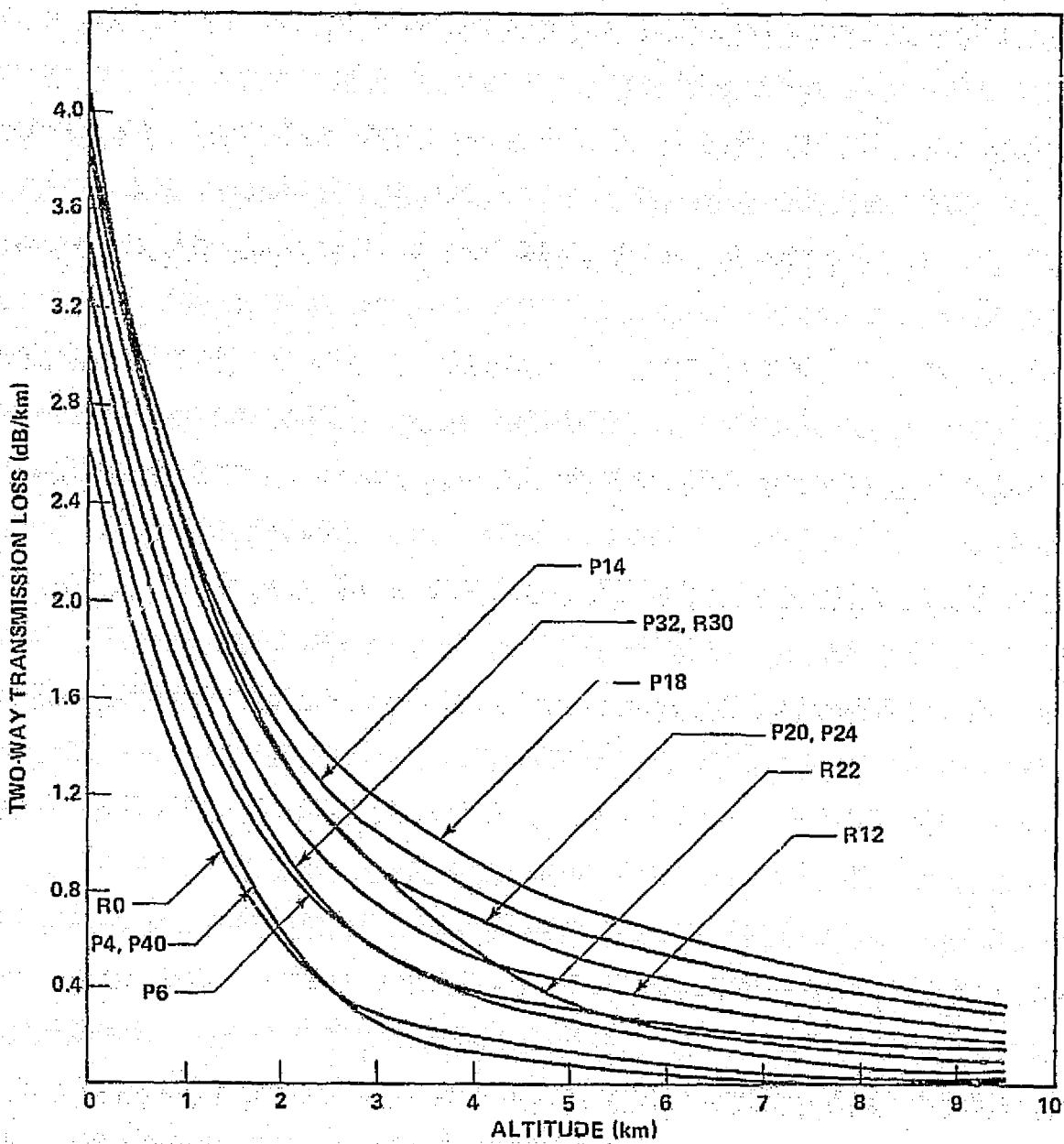


Figure 2. Variation of two-way transmission loss with altitude for P and R lines of CO<sub>2</sub> laser in AFCRL Midlatitude Summer Hazy Atmosphere.

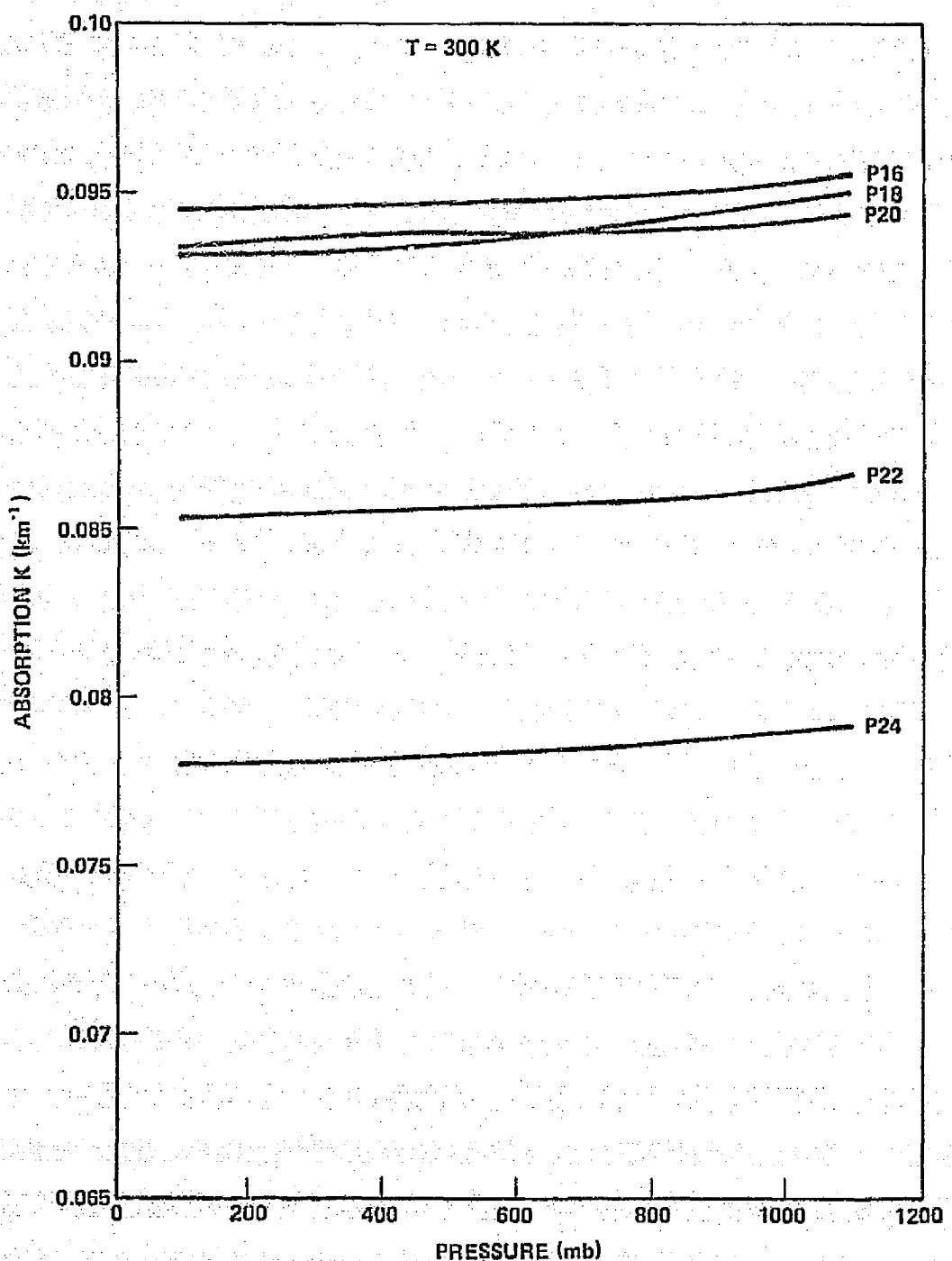


Figure 3. Absorption coefficient of carbon dioxide at  $T = 300 \text{ K}$ .

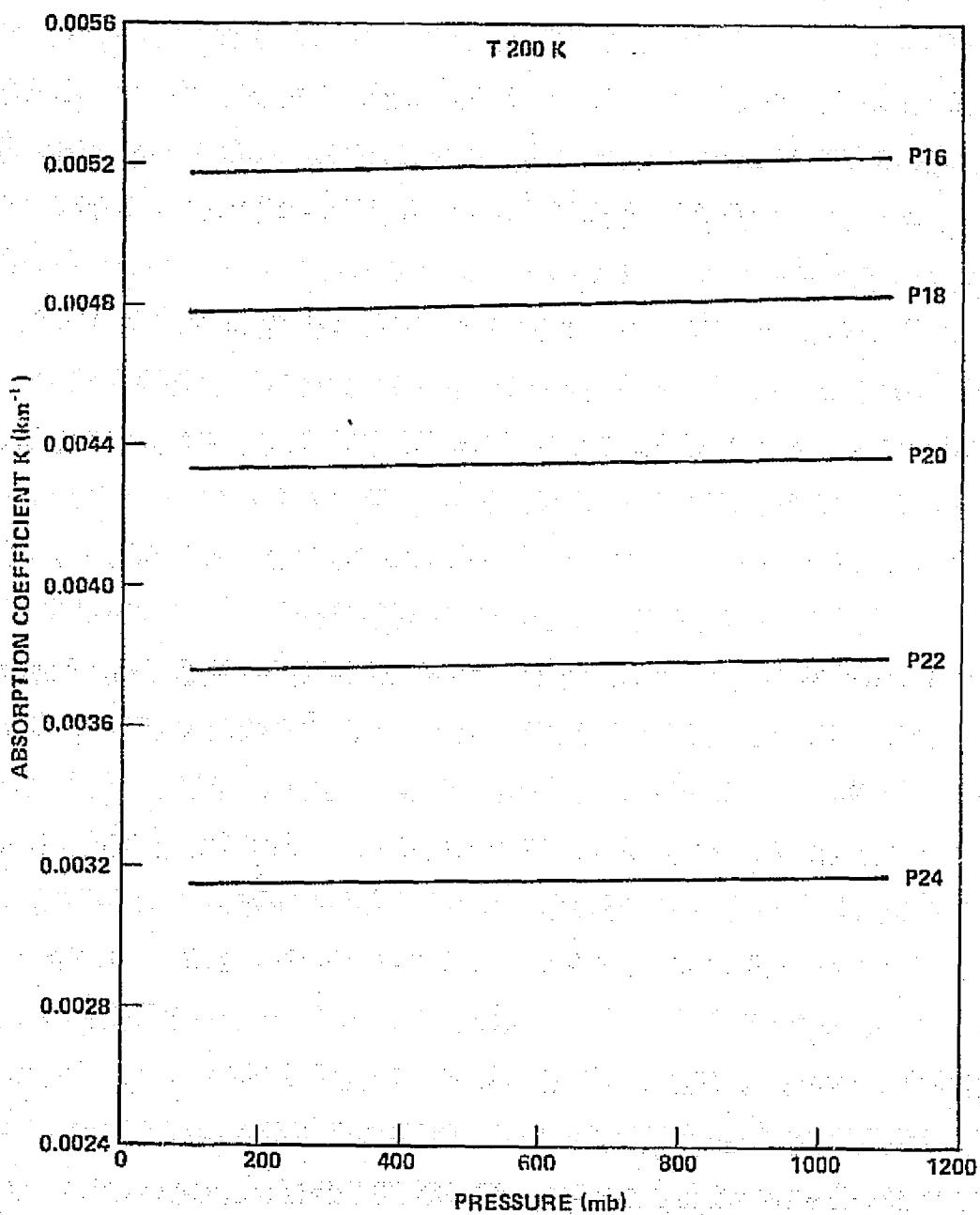


Figure 4. Absorption coefficient of carbon dioxide at  $T = 200 \text{ K}$ .

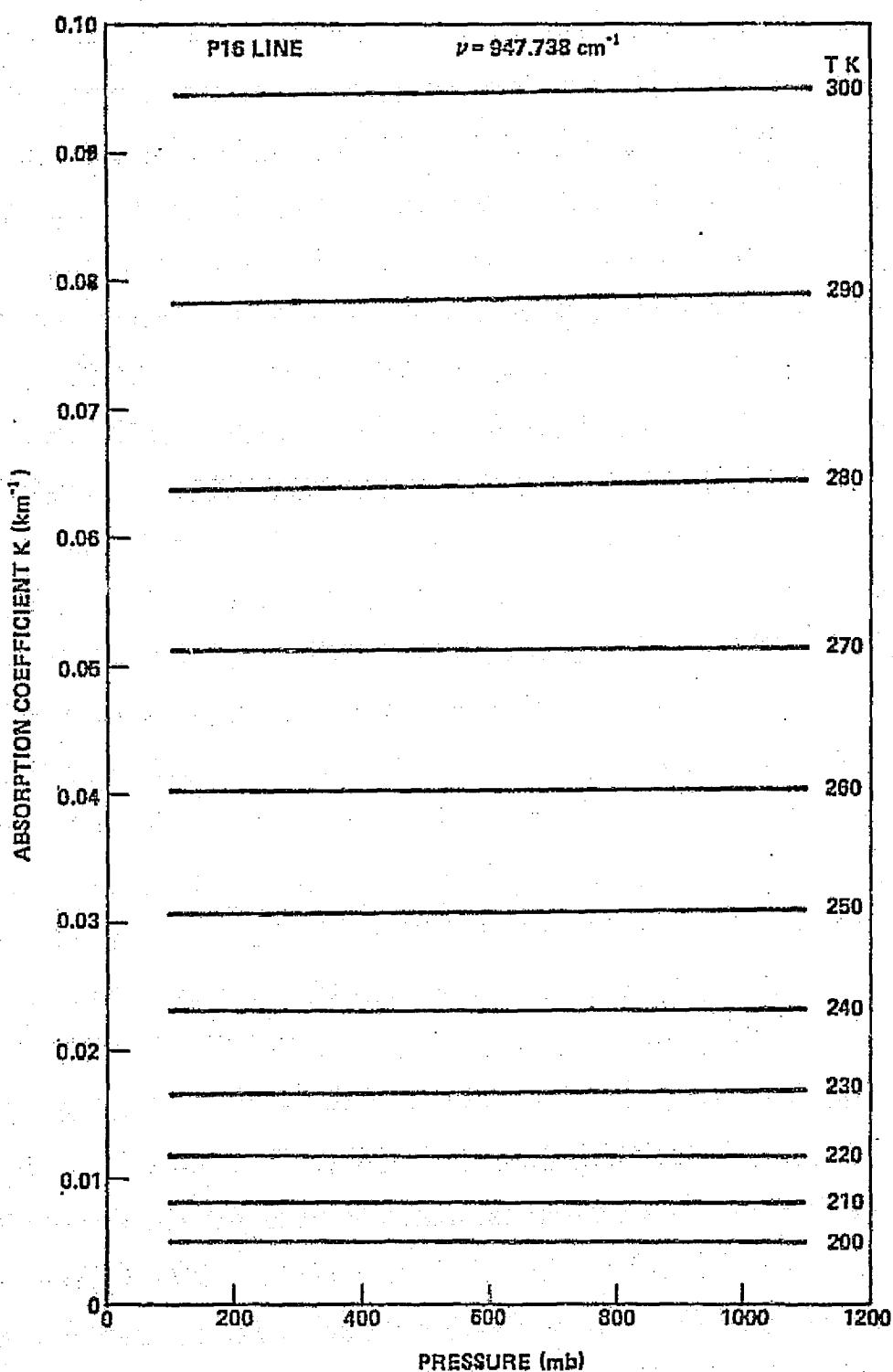


Figure 5. Absorption coefficient of carbon dioxide  
at  $\nu = 947.738 \text{ cm}^{-1}$ .

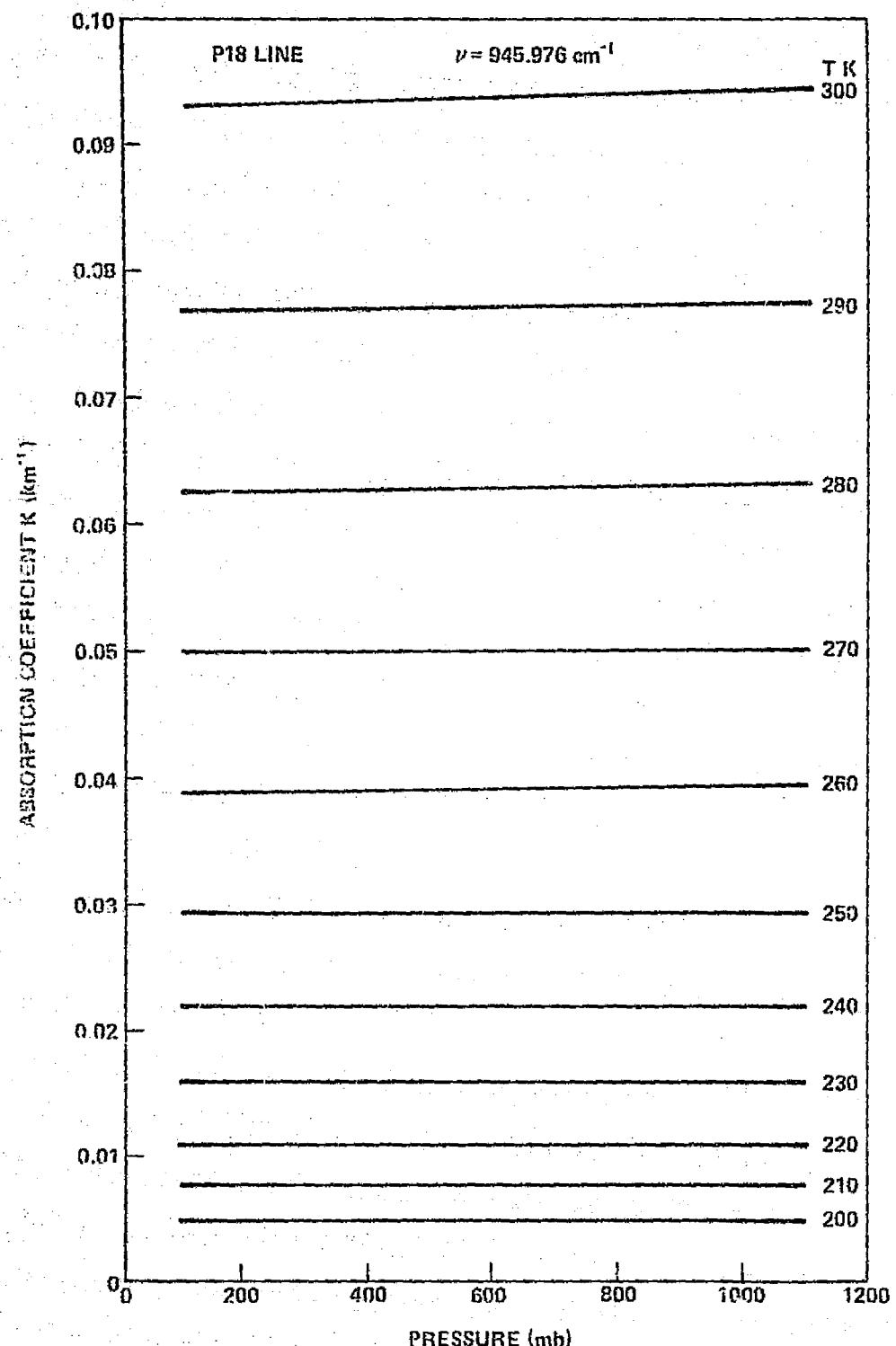


Figure 6. Absorption coefficient of carbon dioxide  
at  $\nu = 945.976 \text{ cm}^{-1}$ .

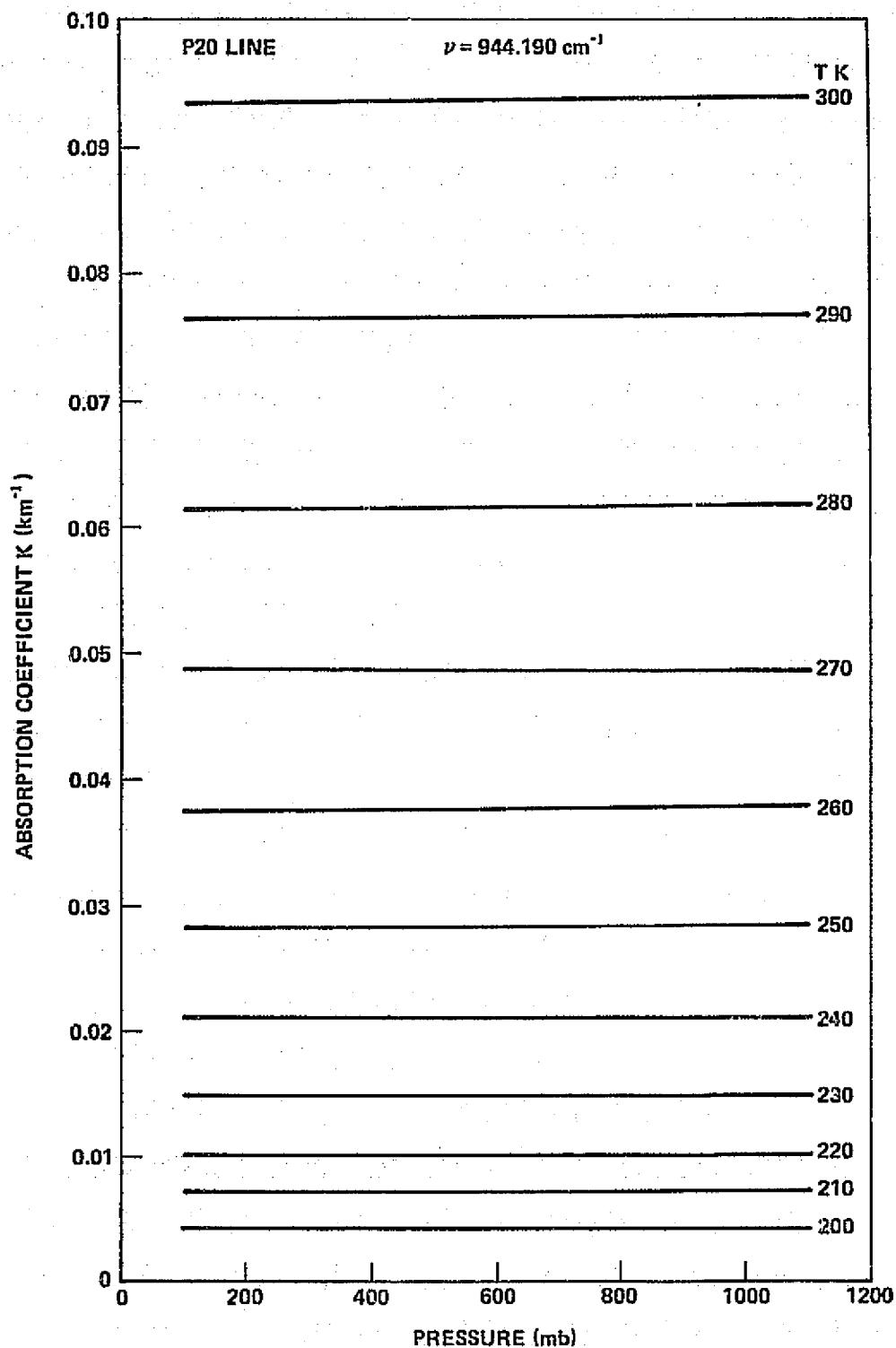


Figure 7. Absorption coefficient of carbon dioxide at  $\nu = 944.190 \text{ cm}^{-1}$ .

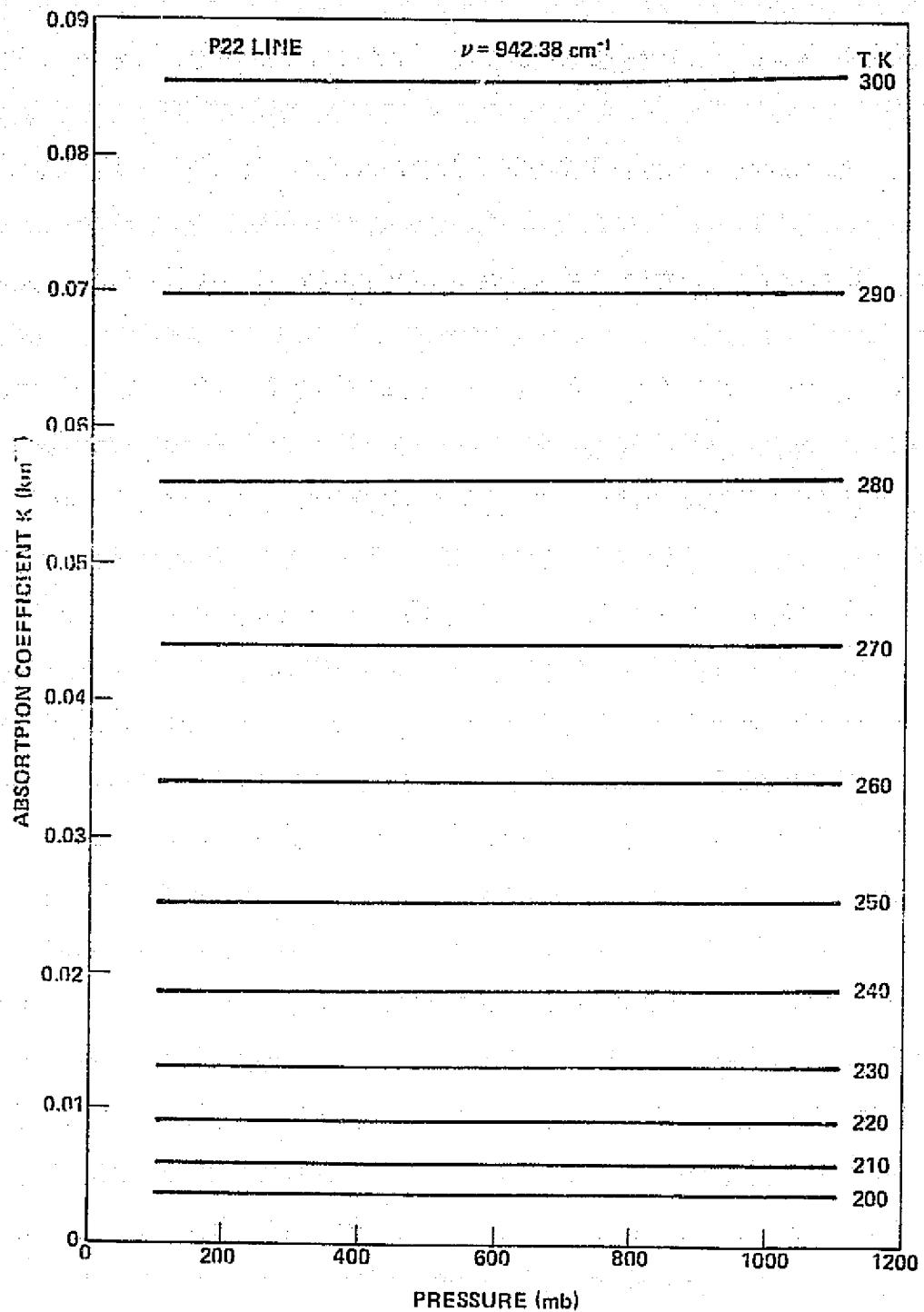


Figure 8. Absorption coefficient of carbon dioxide  
at  $\nu = 942.38 \text{ cm}^{-1}$ .

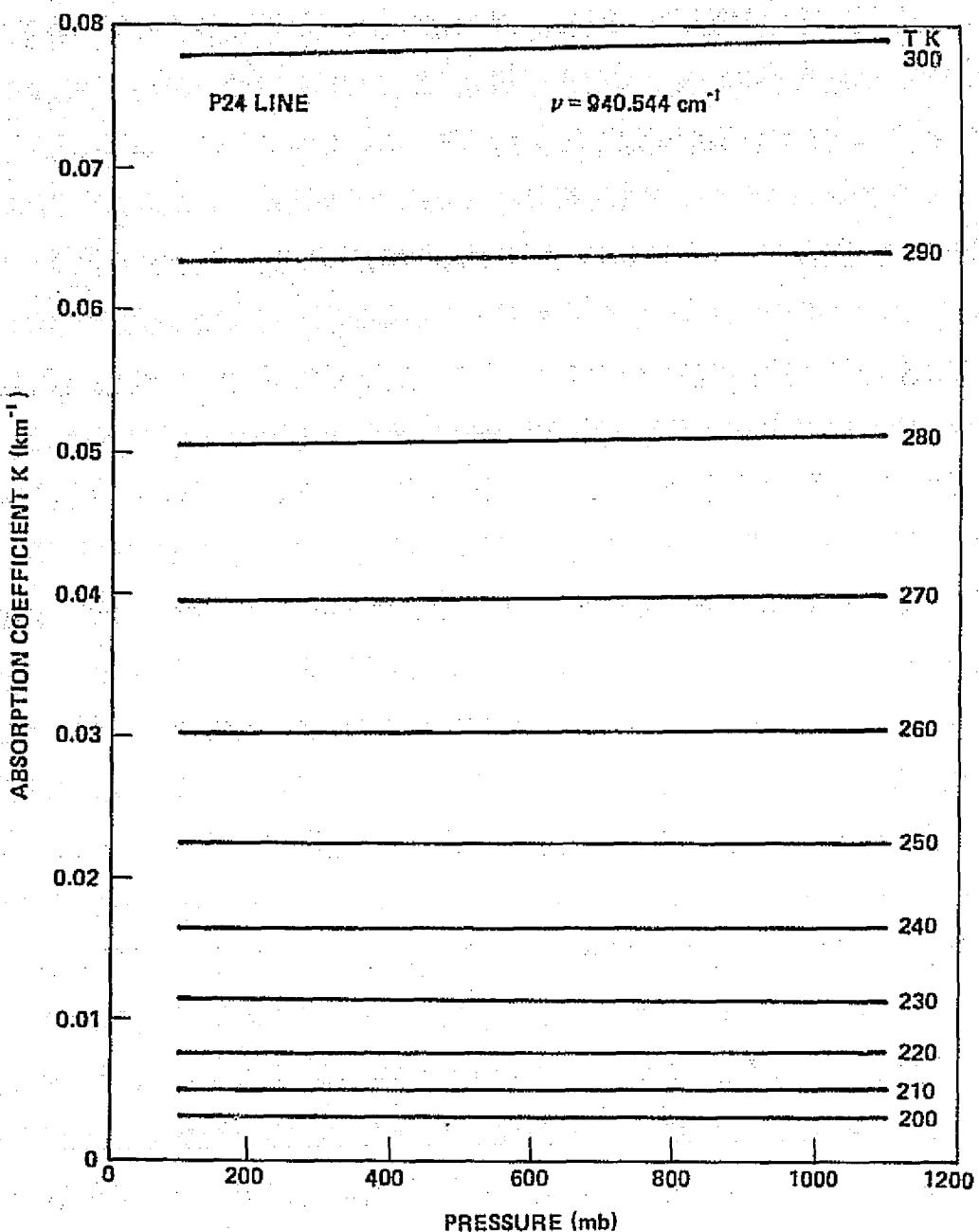


Figure 9 . Absorption coefficient of carbon dioxide at  $\nu = 940.544 \text{ cm}^{-1}$ .

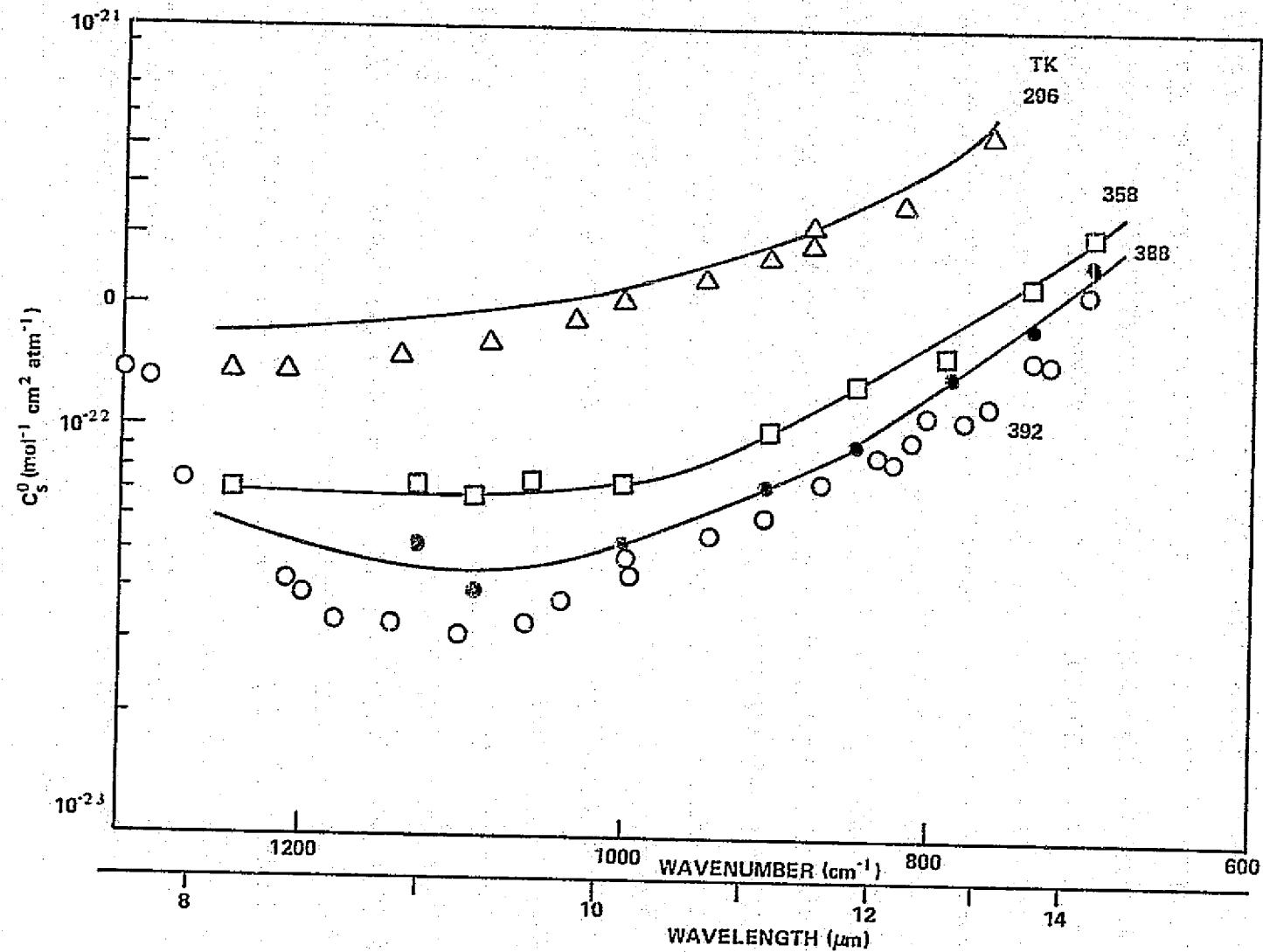


Figure 10. Continuum absorption coefficient of  $\text{H}_2\text{O}$  at different temperatures [15].

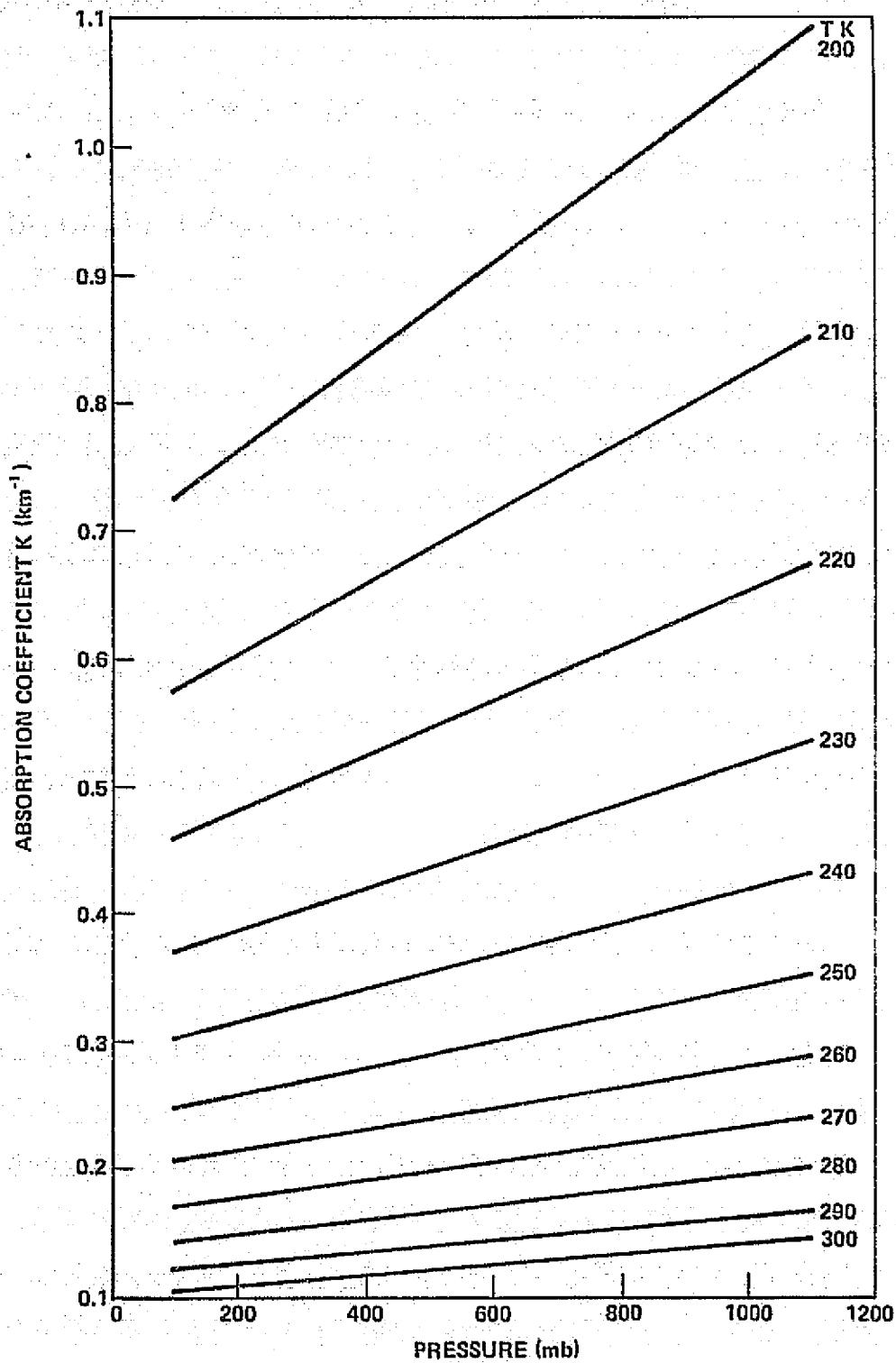


Figure 11. Absorption coefficient of water vapor continuum for 1 PR-CM at  $10.6 \mu\text{m}$ .

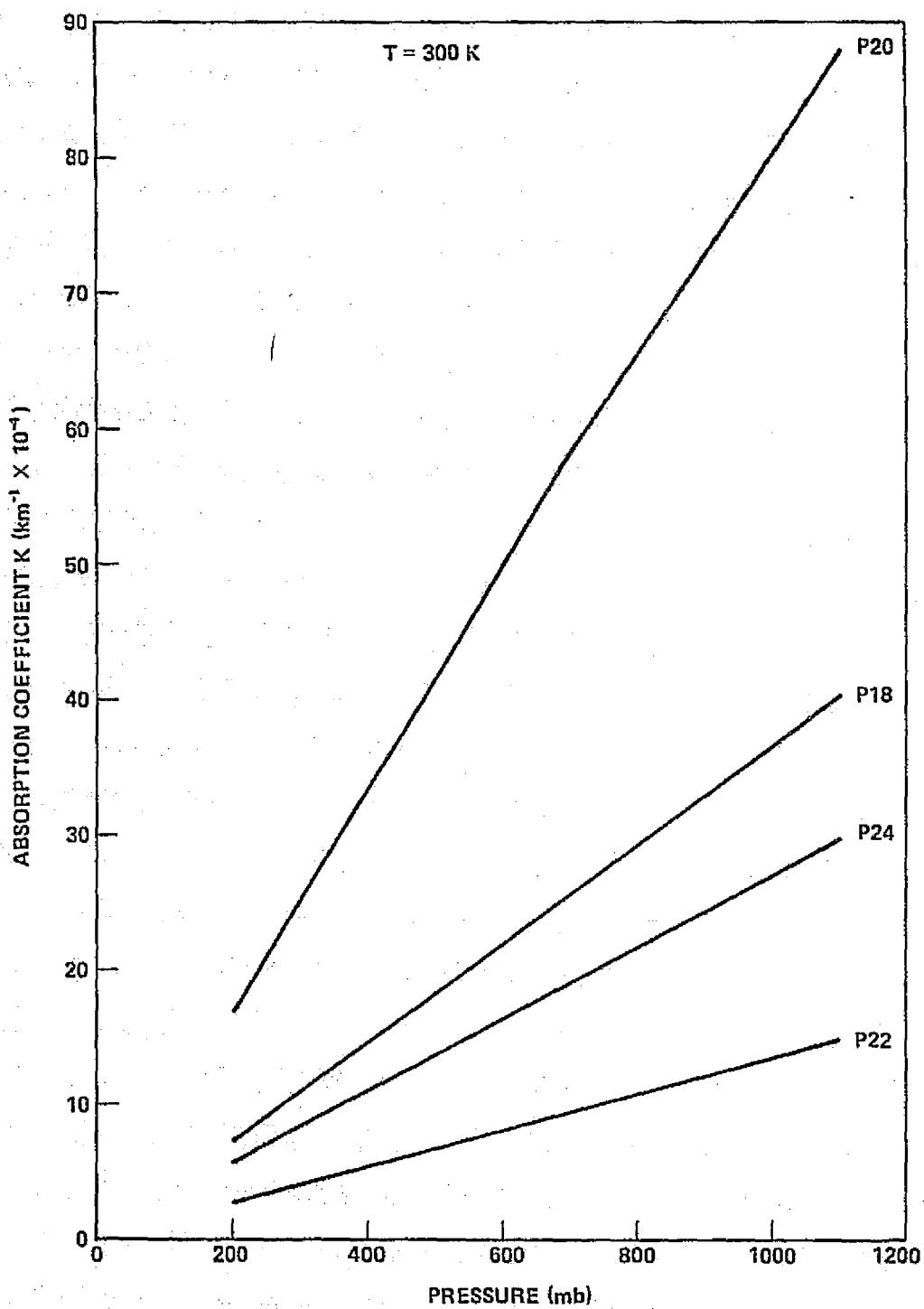


Figure 12. Absorption coefficient of 1 PR-CM of water vapor lines at  $T = 300 \text{ K}$ .

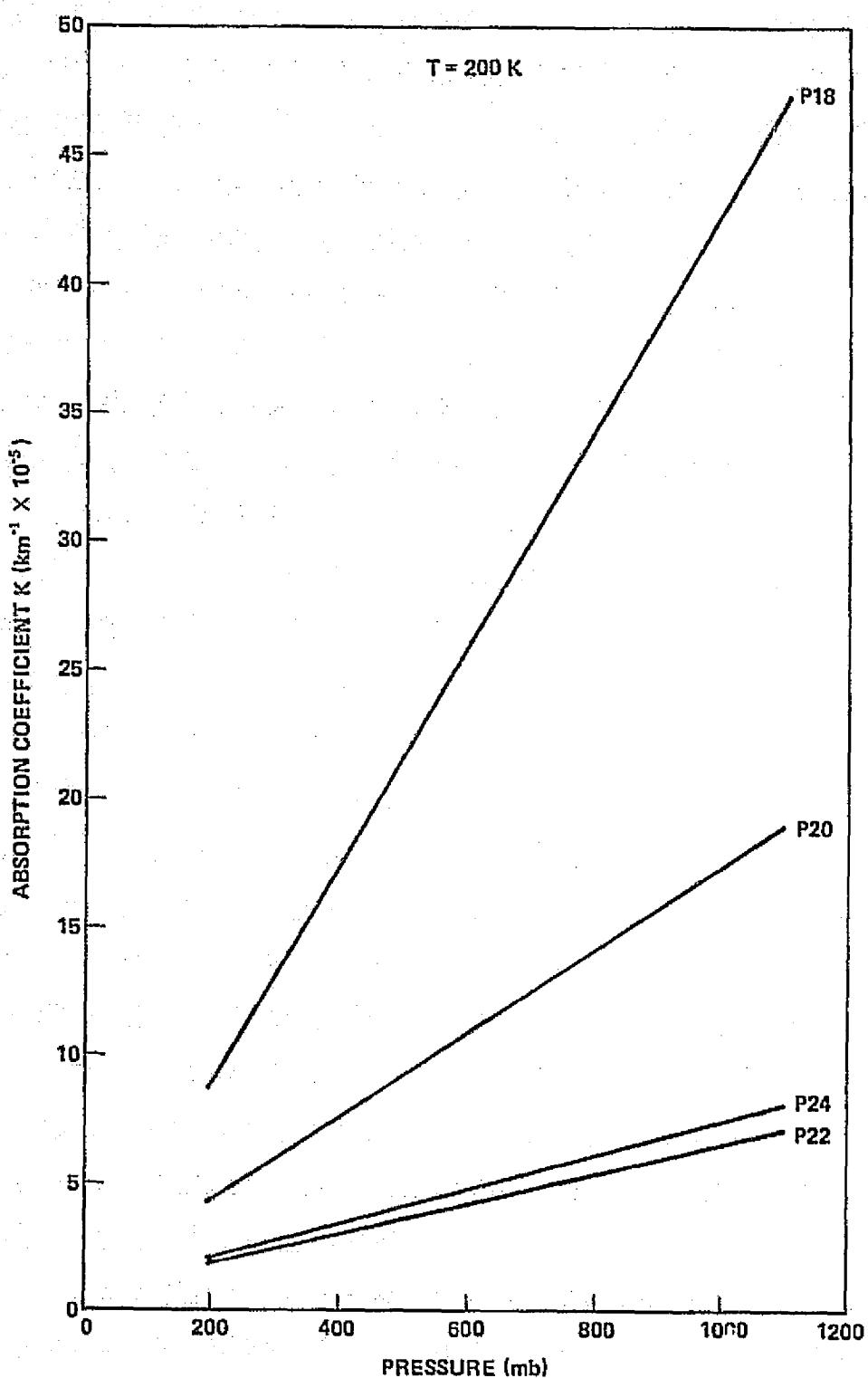


Figure 13. Absorption coefficient of 1 PR-CM of water vapor lines at  $T = 200 \text{ K}$ .

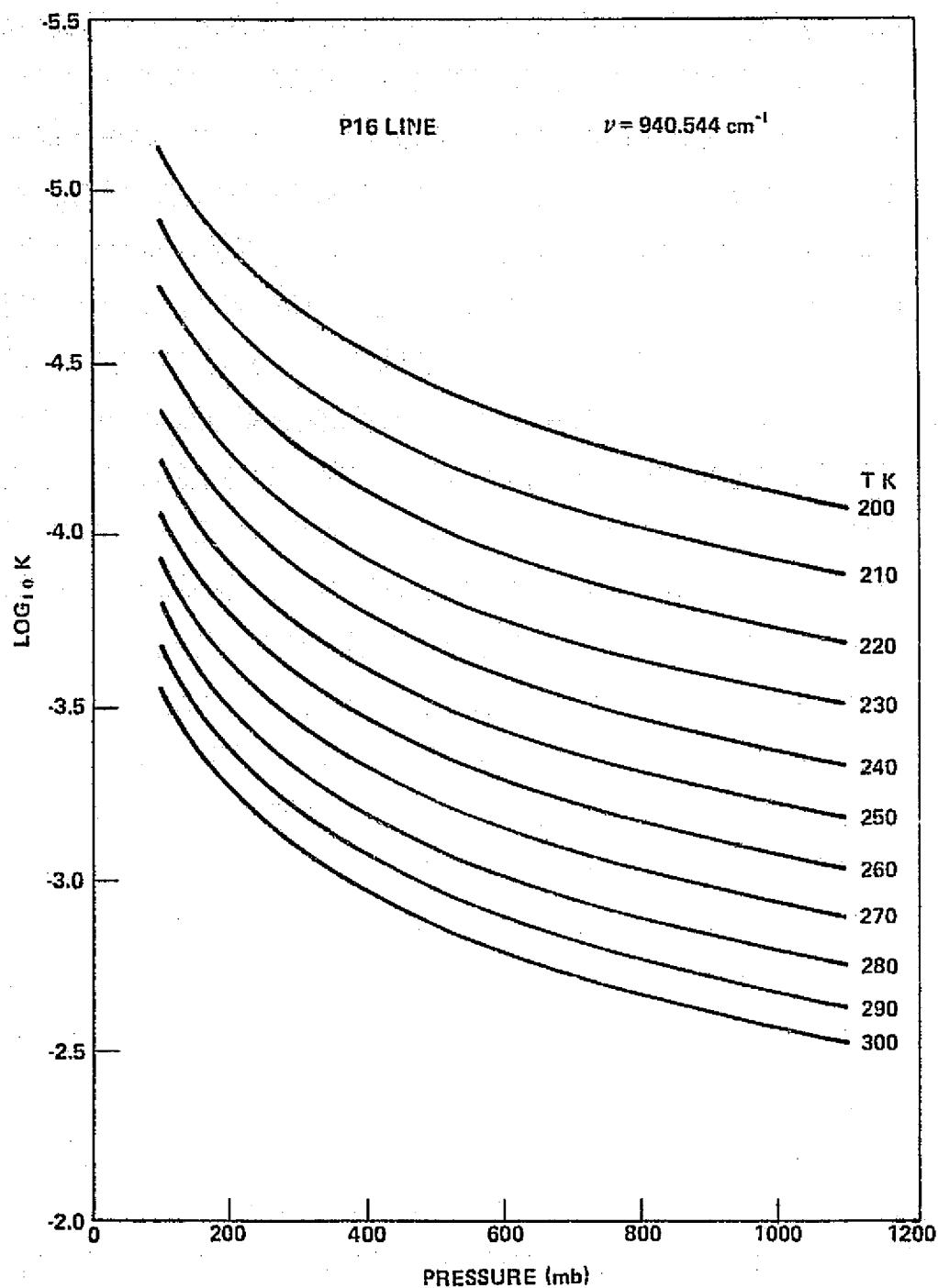


Figure 14. Absorption coefficient of water vapor lines  
at  $\nu = 940.544 \text{ cm}^{-1}$  for 1 PR-CM.

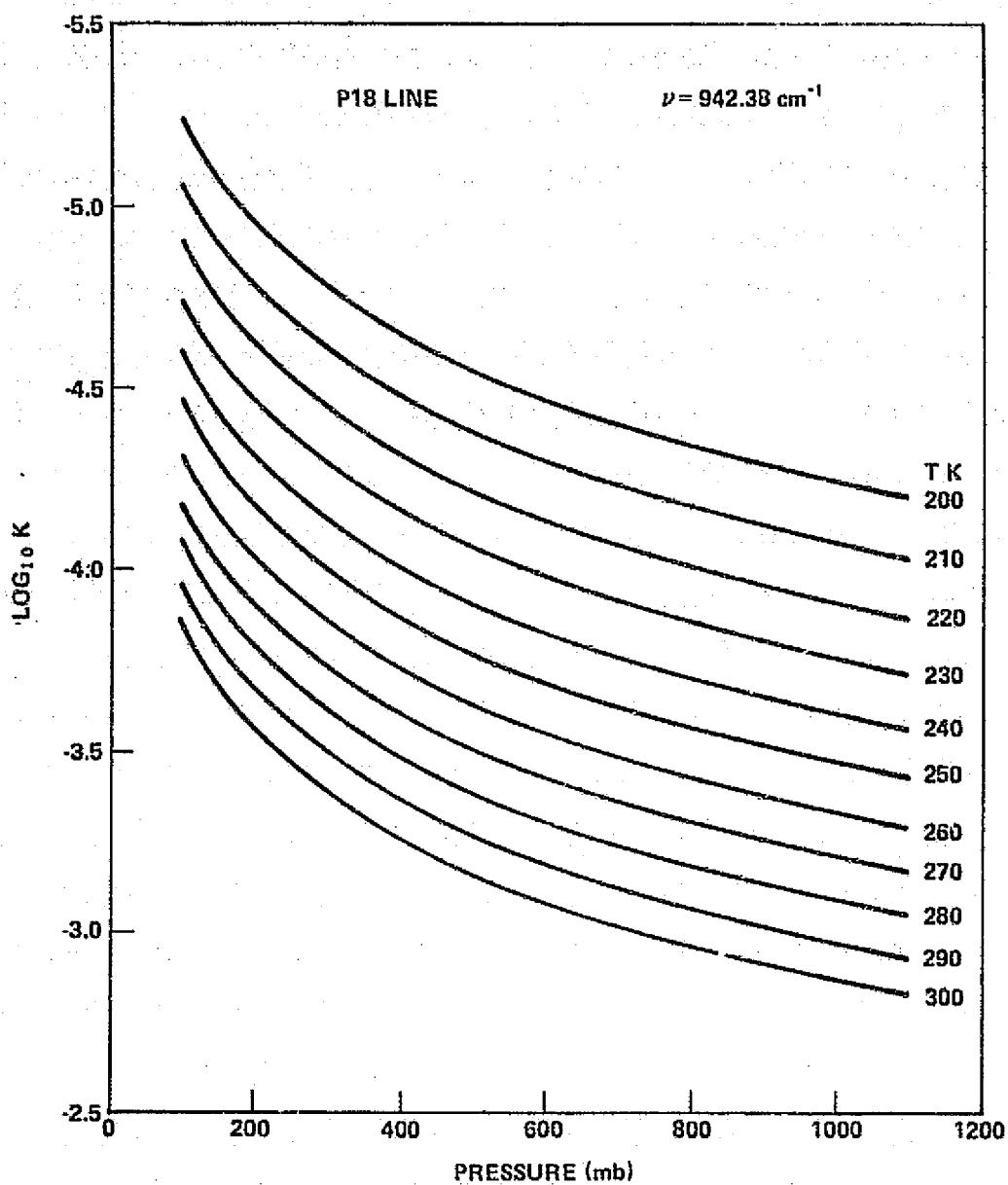


Figure 15. Absorption coefficient of water vapor lines  
at  $\nu = 942.38 \text{ cm}^{-1}$  for 1 PR-CM.

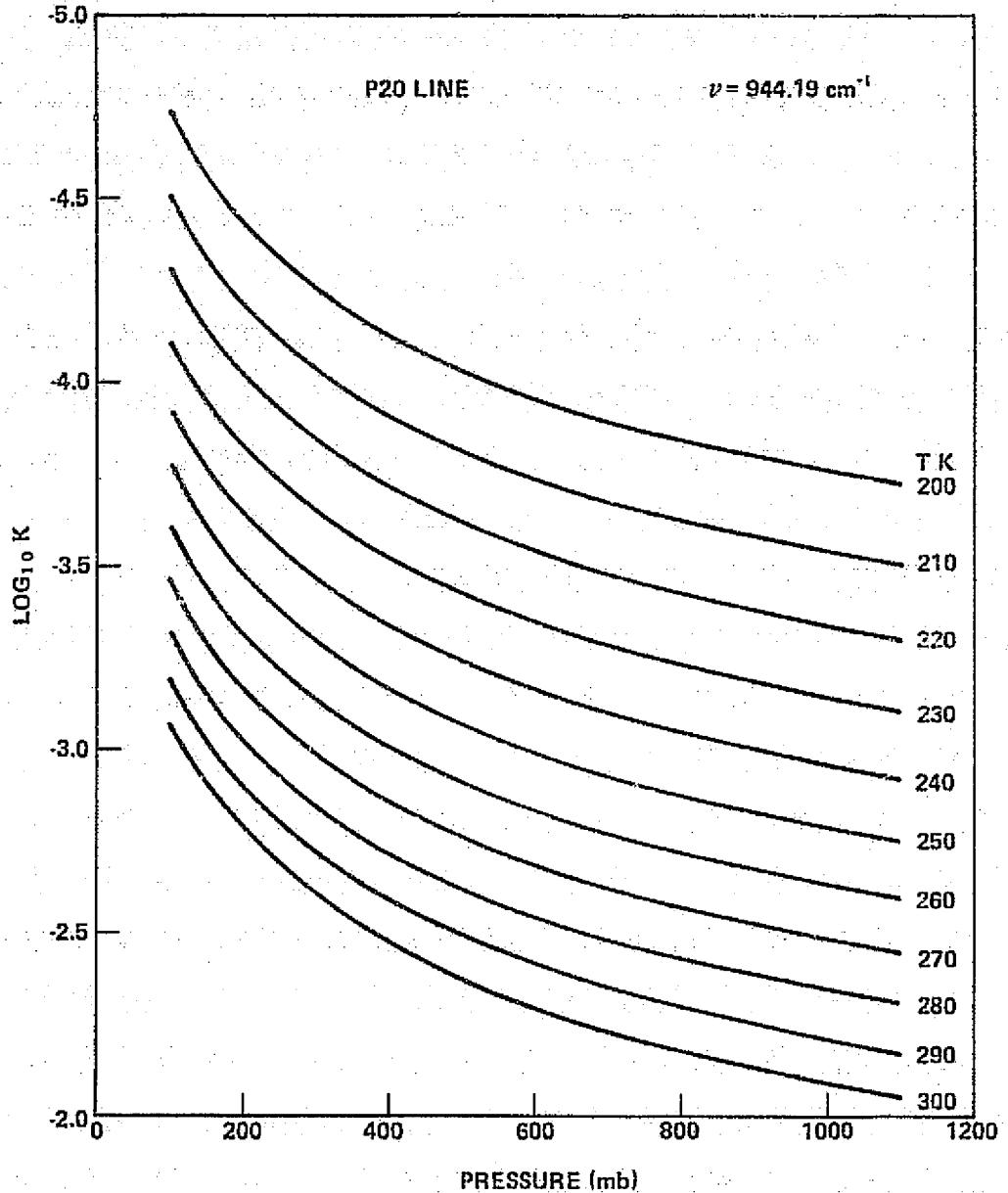


Figure 16. Absorption coefficient of water vapor lines  
at  $\nu = 944.19 \text{ cm}^{-1}$  for 1 PR-CM.

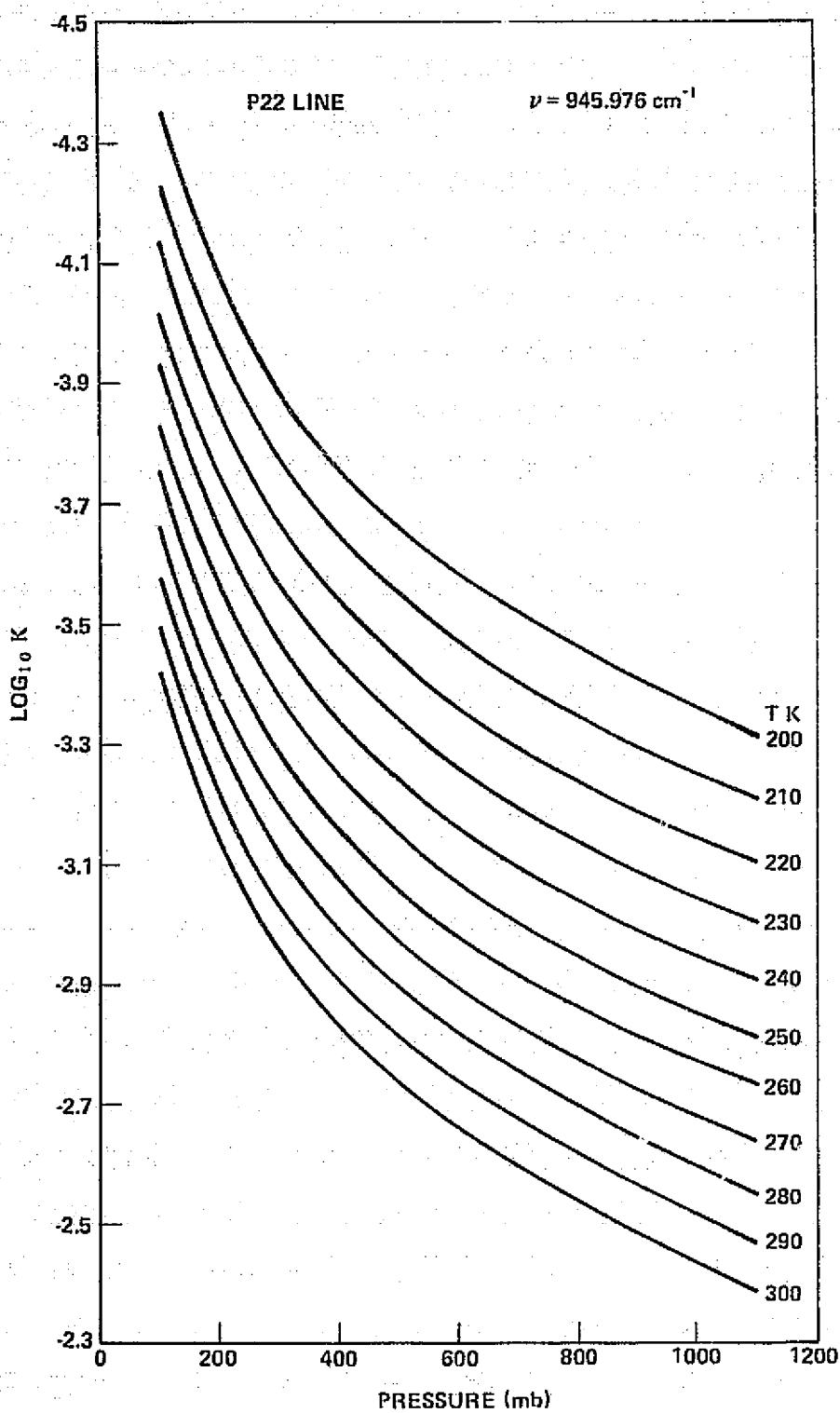


Figure 17. Absorption coefficient of water vapor lines at  $\nu = 945.976 \text{ cm}^{-1}$  for 1 PR-CM.

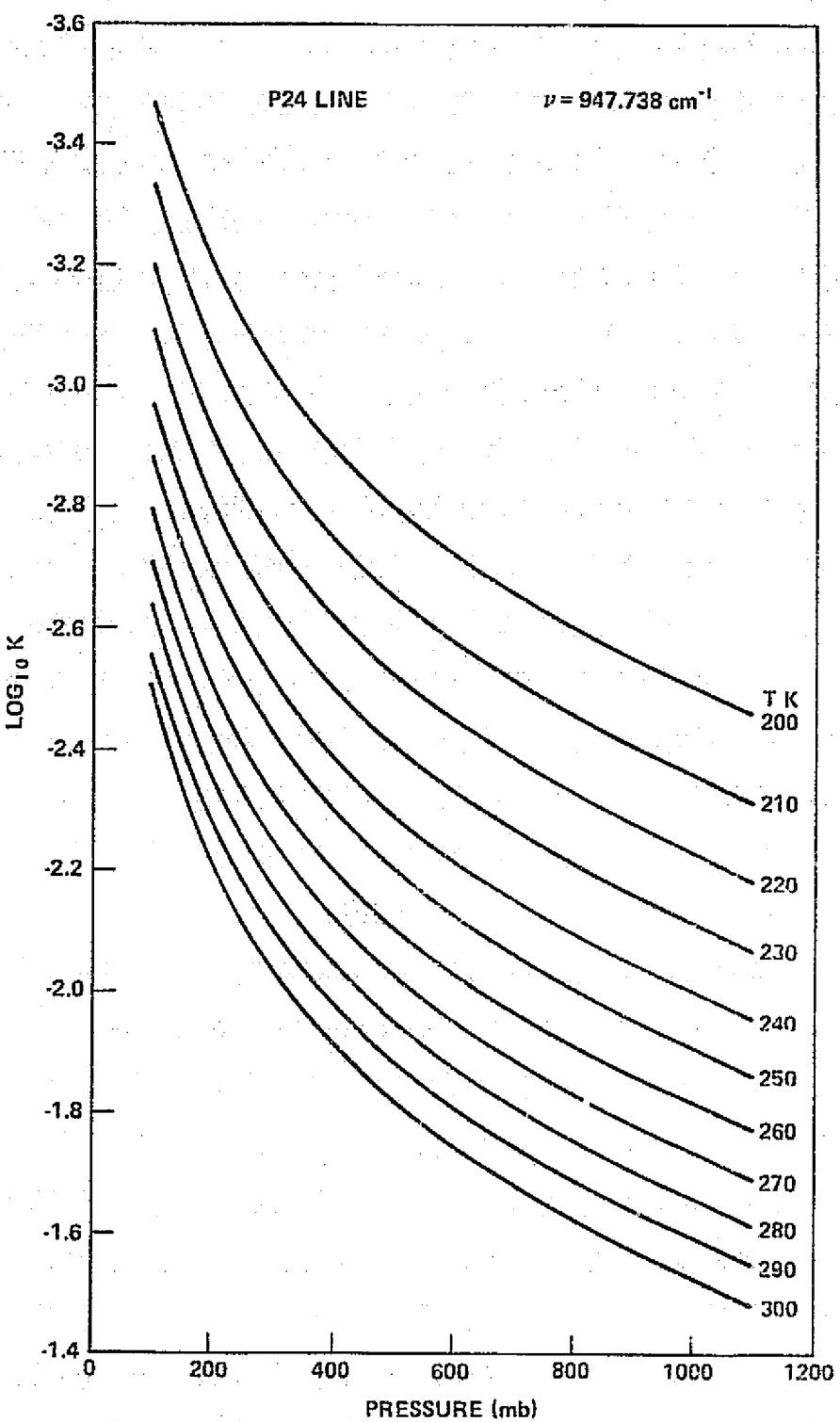


Figure 18. Absorption coefficient of water vapor lines at  $\nu = 947.738 \text{ cm}^{-1}$  for 1 PR-CM.

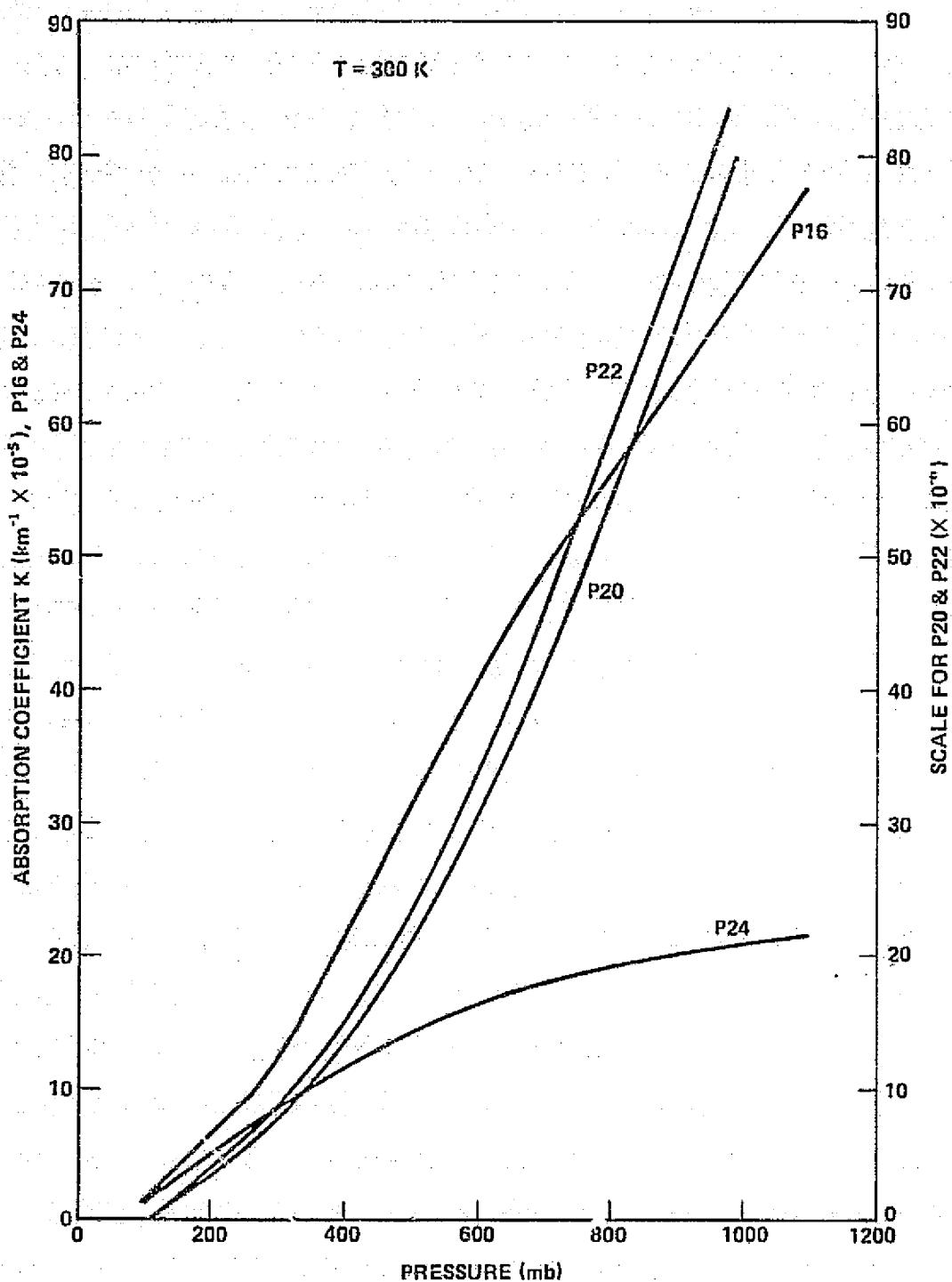


Figure 19. Absorption coefficient of nitrous oxide lines at  $T = 300 \text{ K}$ .

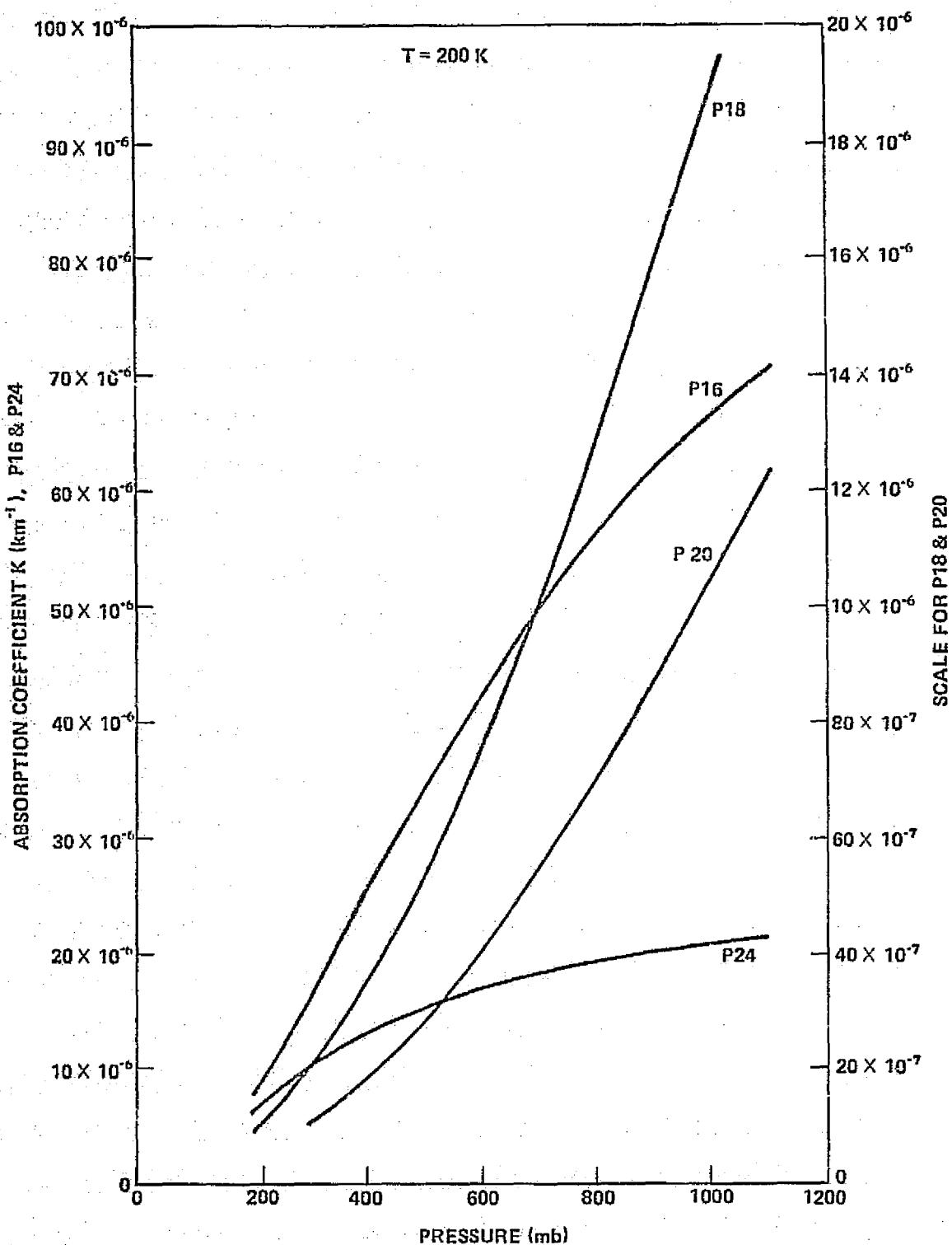


Figure 20. Absorption coefficient of nitrous oxide at  $T = 200 \text{ K}$ .

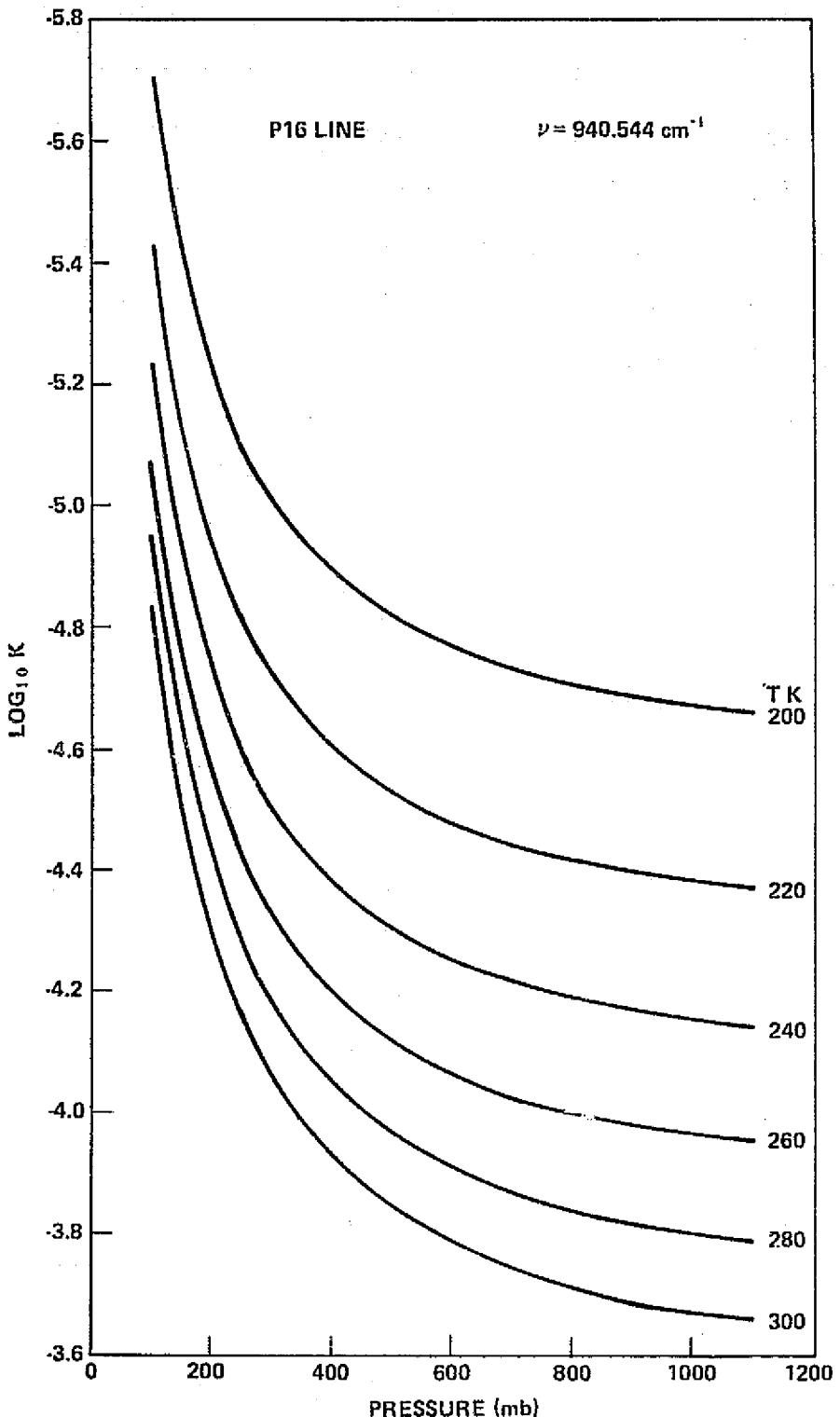


Figure 21. Absorption coefficient of nitrous oxide lines at  $\nu = 940.544 \text{ cm}^{-1}$ .

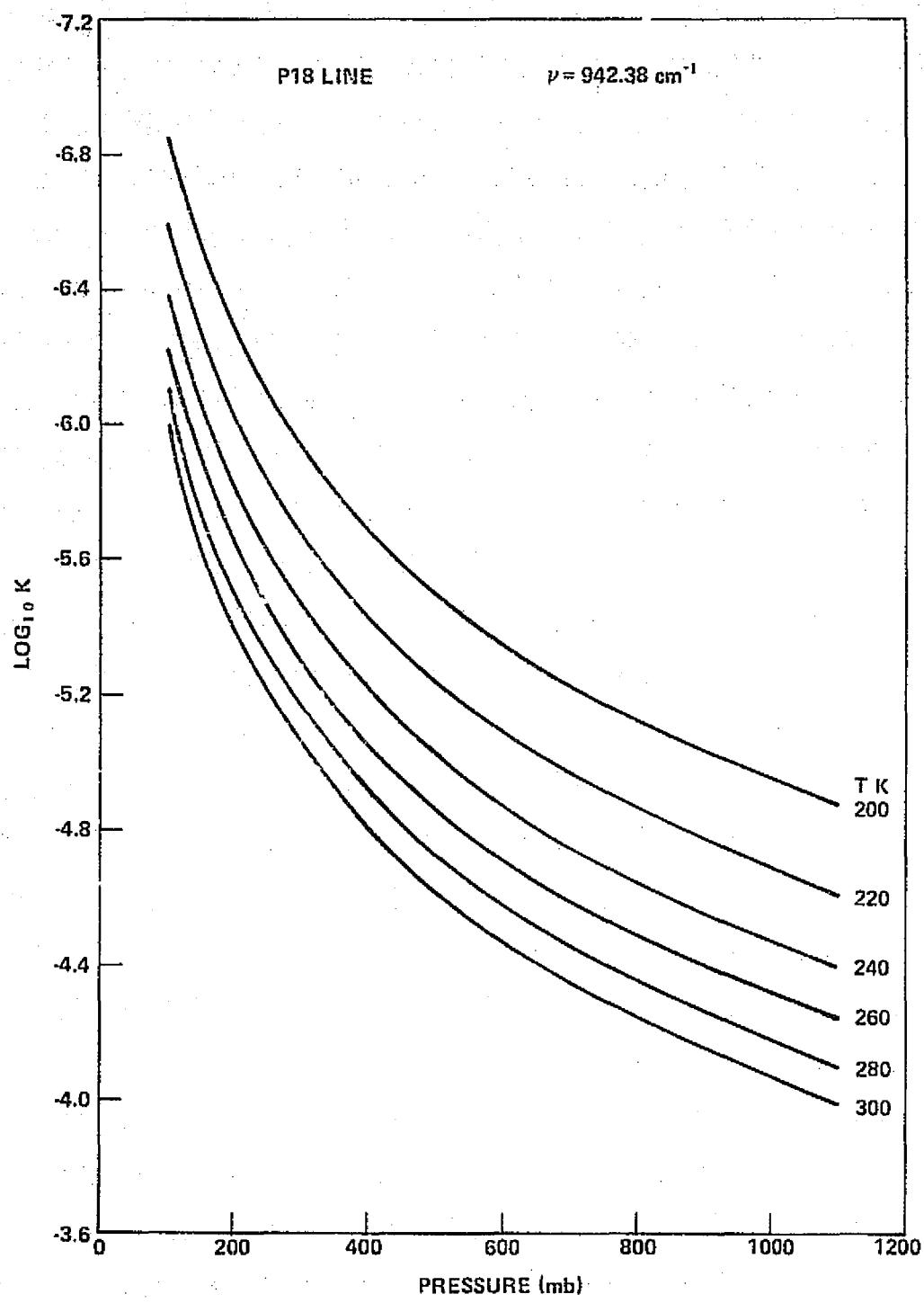


Figure 22. Absorption coefficient of nitrous oxide  
at  $\nu = 942.38 \text{ cm}^{-1}$ .

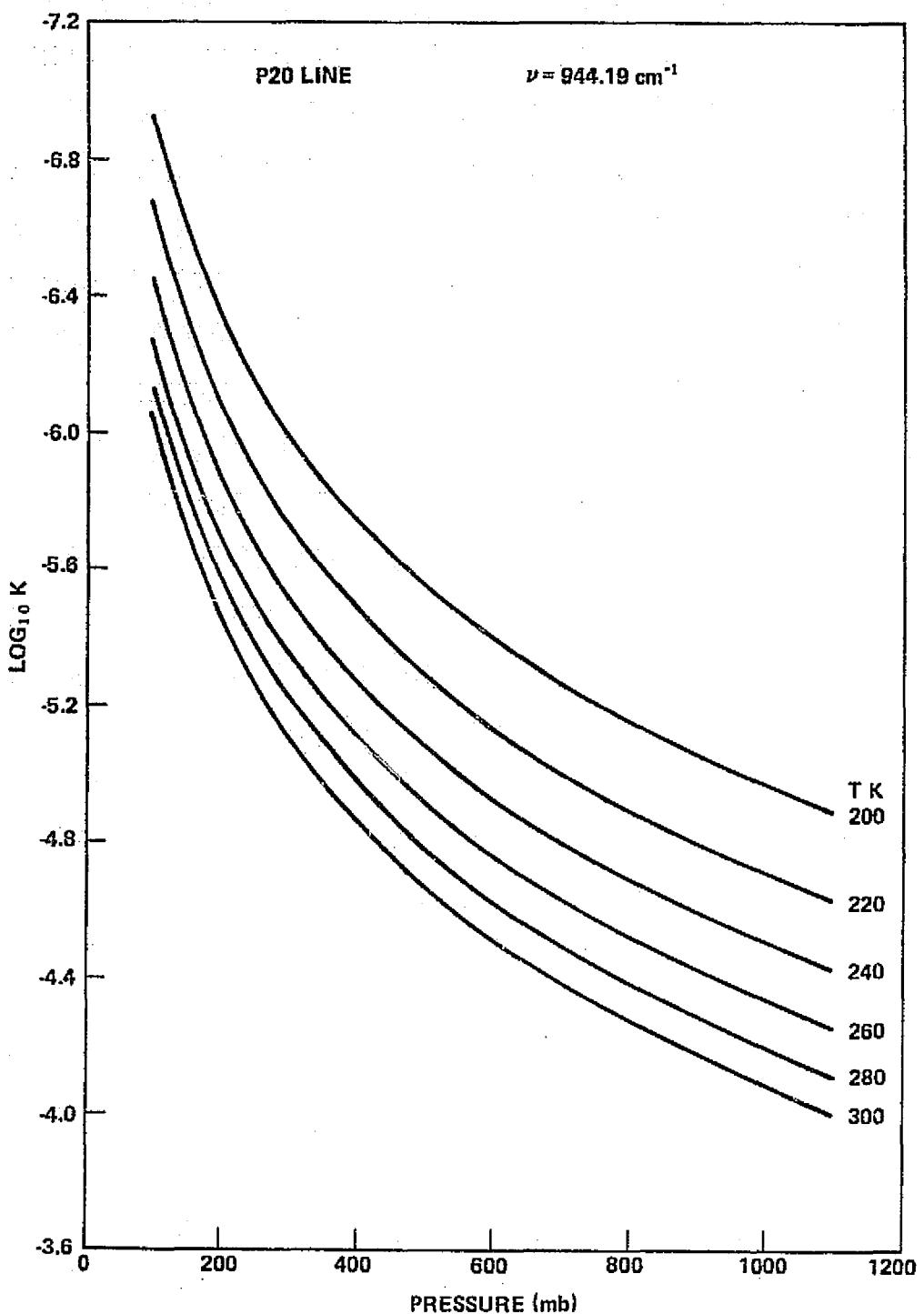


Figure 23. Absorption coefficient of nitrous oxide lines at  $\nu = 944.19 \text{ cm}^{-1}$ .

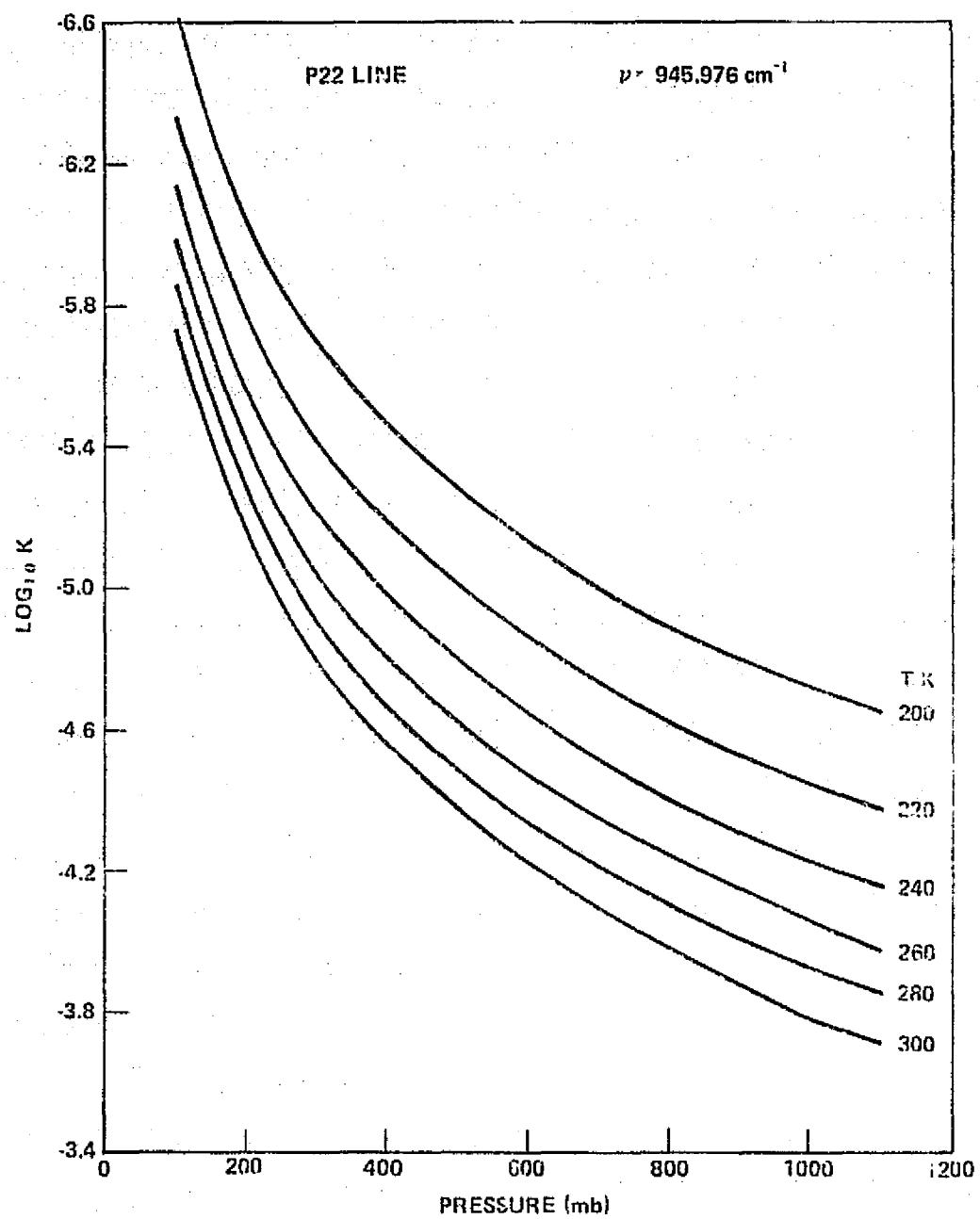


Figure 24. Absorption coefficient of nitrous oxide lines  
at  $\nu = 945.976 \text{ cm}^{-1}$ .

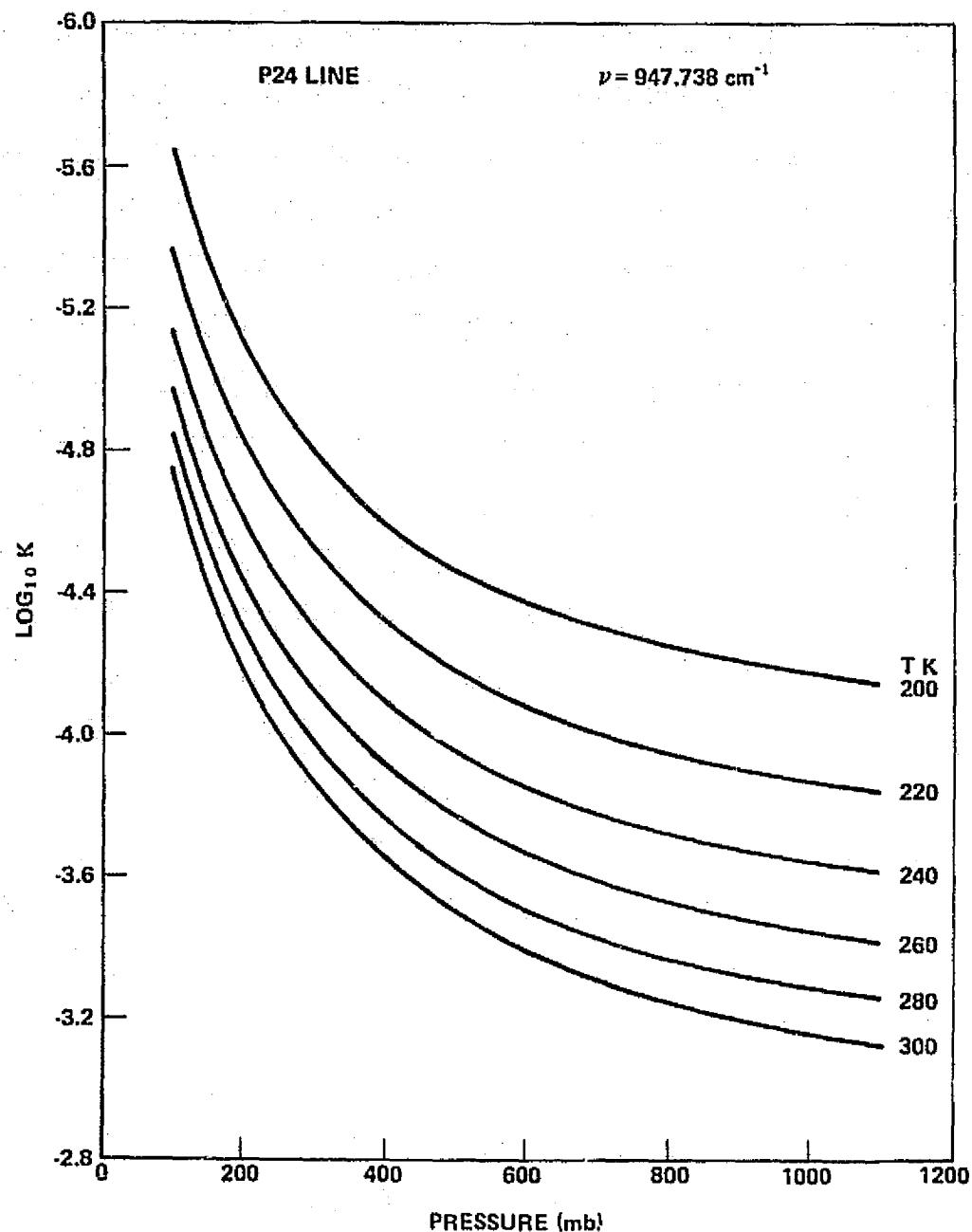


Figure 25. Absorption coefficient of nitrous oxide lines at  $\nu = 947.738 \text{ cm}^{-1}$ .

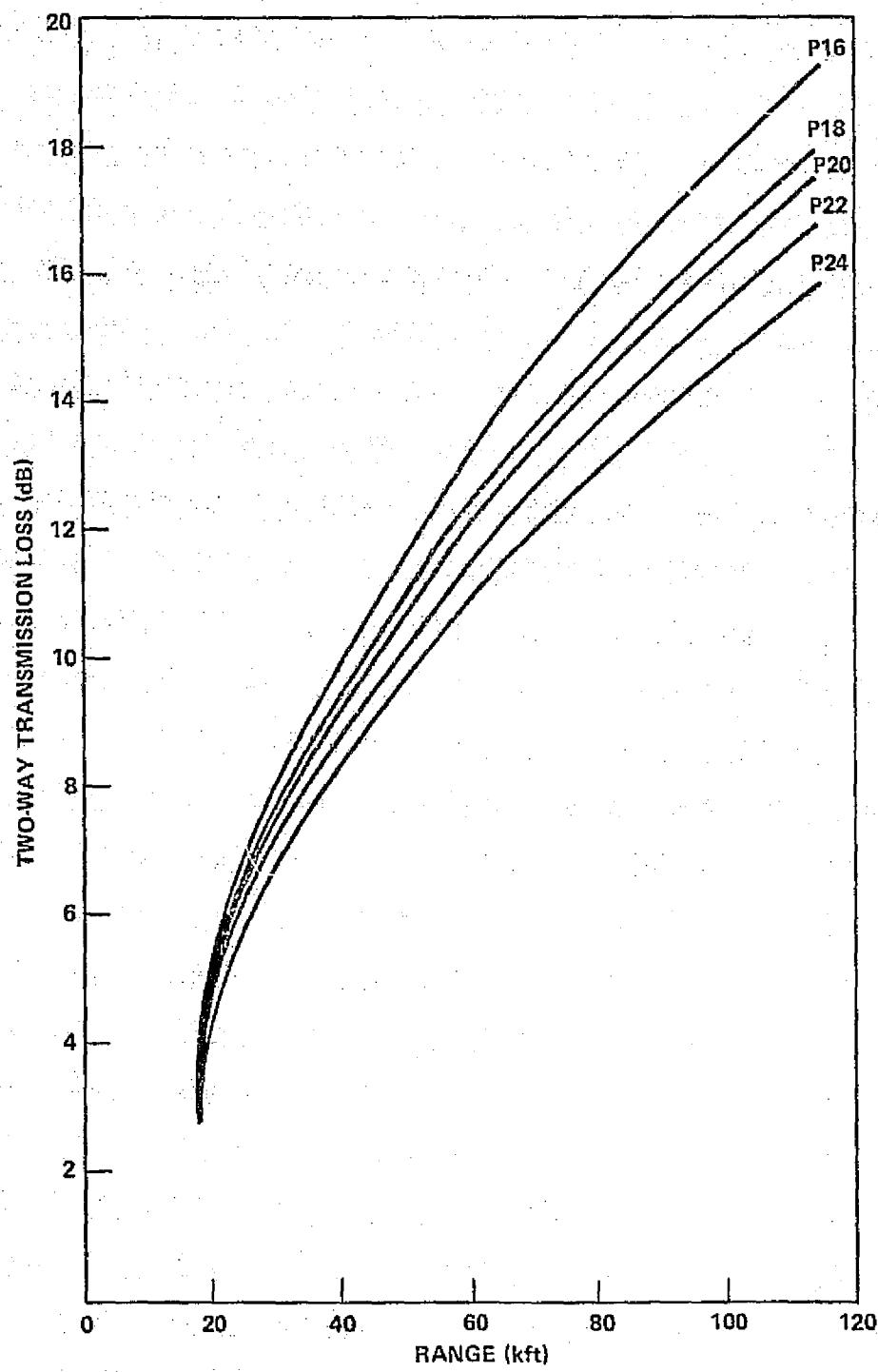


Figure 26. Total transmission loss at the P lines for flight B8,  
run 18, 1/19/1973 at Edwards AFB.

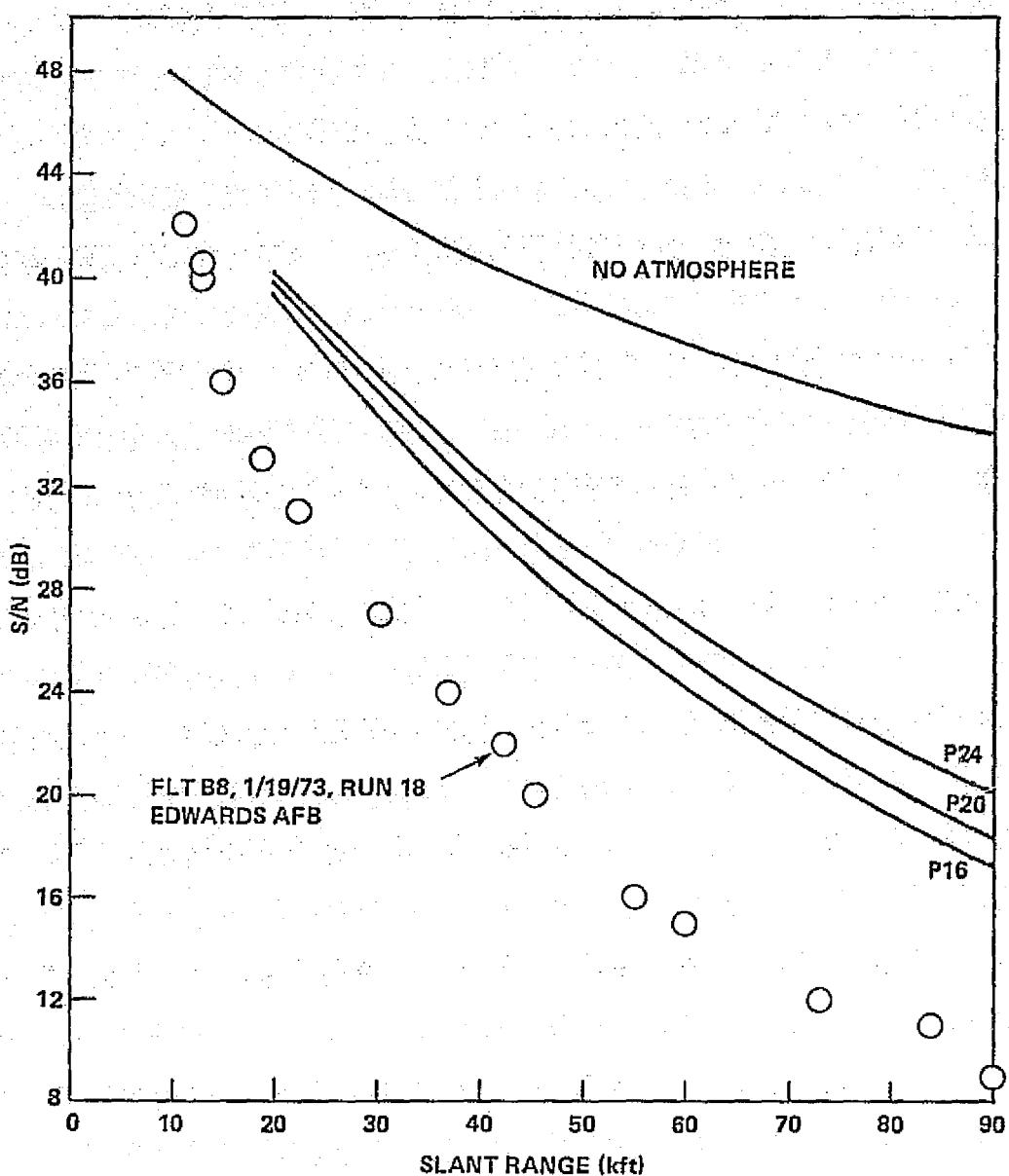


Figure 27. Comparison of measured and theoretical S/N values.

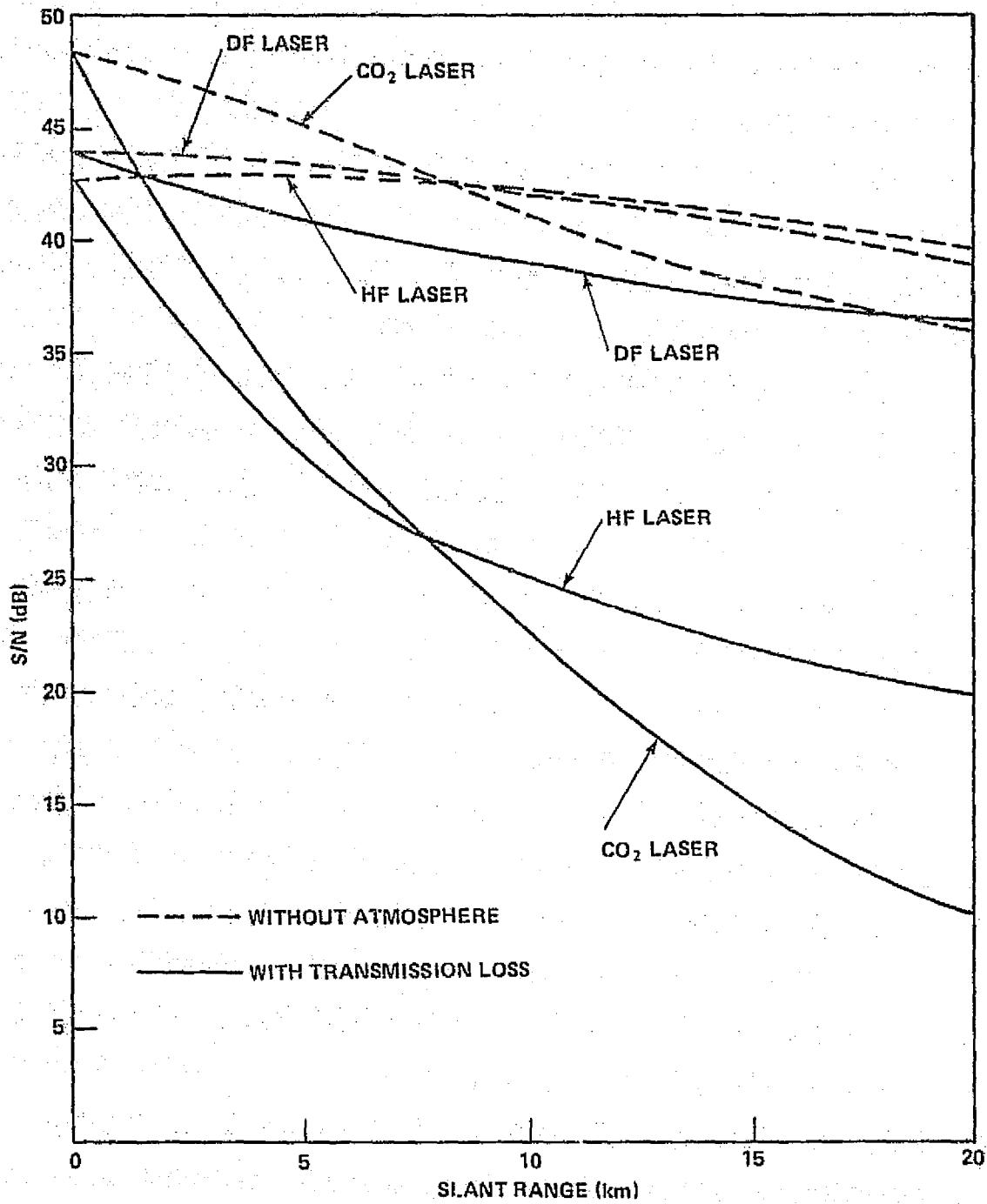


Figure 28. Performance of CO<sub>2</sub>, HF and DF laser Doppler systems against ground target at 15° inclination in AFCRL Midlatitude Summer Atmosphere.

## REFERENCES

1. Howard, J. N.; King, J. I. F.; and Gast, P. R.: Thermal Radiation, Handbook of Geophysics, United States Air Force; Geophysics Research Directorate, the Macmillan Company, New York, Chapter 16, 1960.
2. McClatchey, R. A. and Selby, J. E. A. Atmospheric Transmission, 7-30  $\mu\text{m}$ : Attenuation of CO<sub>2</sub> Laser Radiation, AFCRL-72-0611, 12 October 1972, Air Force Cambridge Research Laboratories, Bedford, Massachusetts.
3. Benedict, W.S. and Kaplan, L.D.: Calculation of Line Widths in H<sub>2</sub>O-N<sub>2</sub> Collisions. Journal of Chemical Physics, vol. 30, 1959, p. 388.
4. Ely, R. and McCubbin, T.K.: The Temperature Dependence of the Self-Broadened Half-Width of the P-20 Line in the 001-100 Band of CO<sub>2</sub>. Applied Optics, vol. 9, no. 5, 1970, p. 1230.
5. Tubbs, L.D. and Williams, D.: Broadening of Infrared Absorption lines at Reduced Temperatures: Carbon Dioxide. J. Optical Society of America, vol. 62, 1972, p. 284.
6. McClatchey, R. A.; Benedict, W.S.; Clough, S. A.; Burch, D. E.; Calfee, R. F.; Fox, K.; Rothman, L. S.; and Garing, J. S.: AFCRL Atmospheric Absorption Line Parameter Compilation, AFCRL-TR-73-0096, 26 January 1973, Air Force Cambridge Research Laboratories, Bedford, Massachusetts.
7. Yin, P.K.L and Long, R.K.: Atmospheric Absorption at the Line Center of P(20) CO<sub>2</sub> Laser Radiation. Applied Optics, vol. 8, August 1968, p. 1551.
8. Elsasser, W.M.: Note on Atmospheric Absorption Caused by the Rotational Water Band. Physical Review, vol. 53, 1938, p. 768.
9. Yates, H. W. and Taylor, J. H.: Infrared Transmission of the Atmosphere, NRL Report 5453, 1960.
10. Anthony, R.: Atmospheric Absorption of Solar Infrared Radiation. Physical Review, vol. 85, 1952, p. 674.

## REFERENCES (Continued)

11. Roach, W. T. and Goody, R. W.: Absorption and Emission in the Atmospheric Window from 770 to 1250  $\text{cm}^{-1}$ . Quarterly J. Royal Meteorological Society, vol. 84, 1958, p. 319.
12. Bignell, K. J.; Saiedy, F.; and Sheppard, P. A.: On the Infrared Continuum. J. Optical Society of America, vol. 53, 1963, p. 466.
13. Bignell, K. J.: The Water-Vapor Infrared Continuum. Quarterly J. Royal Meteorological Society, vol. 96, 1970, p. 390.
14. McCoy, J. H.; Rensch, D. B.; and Long, R. K.: Water Vapor Continuum Absorption of Carbon Dioxide Laser Radiation near 10  $\mu$ . Applied Optics, vol. 8, 1969, p. 1471.
15. Burch, D. E.: Radiative Properties of the Atmospheric Windows. Preprints of Conference on Atmospheric Radiation, Americal Meterological Society, August 1972, p. 61.
16. Burch, D. E.: Private Communication, August 1975.
17. Varanasi, P.; Chou, S.; and Penner, S. S.: Absorption Coefficients for Water Vapor in the 600-1000  $\text{cm}^{-1}$  Region. J. Quantitative Spectroscopy and Radiative Transfer, vol. 8, 1968, p. 1537.
18. Huffaker, R. M.: Laser Doppler Detection Systems for Gas Velocity Measurements. Applied Optics, vol. 9, 1970, p. 1026.
19. Huffaker, R. M.; Jelalian, A. V.; and Thomson, J. A. L.: Laser Doppler System for Detection of Aircraft Trailing Vortices. Proceedings of the IEEE, vol. 58, 1970, p. 322.
20. Huffaker, R. M.: CO<sub>2</sub> Laser Doppler System for the Measurement of Atmospheric Winds and Turbulence. Atmospheric Technology, National Center for Atmospheric Research, Winter 1974-1975, p. 71.
21. Huffaker, R. M. et al: Development of a Laser Doppler System for the Detection, Tracking, and Measurement of Aircraft Wake Vortices. NASA TM-X-66868, NASA-Marshall Space Flight Center, Alabama 35812, and U. S. Department of Transportation, Federal Aviation Admiinstration, Washington, D.C. 20590, March 1975.

## REFERENCES (Concluded)

22. Kawachi, D. A.: Data Analysis of the January 1973 Clear Air Turbulence Laser Flight Tests, Report No. ER 74-4140, December 1973, Raytheon Company, Equipment Division, Sudbury, Massachusetts 01776.
23. Wang, J. Y.: Infrared Atmospheric Transmission of Laser Radiation. Applied Optics, vol. 13, 1974, p. 56.
24. Spencer, D. J.; Denault, G. C.; and Takimoto, H. H.: Atmospheric Gas Absorption at DF Laser Wavelength. Applied Optics, vol. 13, 1974, p. 2855.
25. Rensch, D. B. and Long, R. K.: Comparative Studies of Extinction and Backscattering by Aerosols, Fog and Rain at  $10.6 \mu$  and  $0.63 \mu$ . Applied Optics, vol. 9, 1970, p. 1563.

## APPROVAL

### ATMOSPHERIC TRANSMISSION OF CO<sub>2</sub> LASER RADIATION WITH APPLICATION TO LASER DOPPLER SYSTEMS

By S. S. R. Murty

The information in this report has been reviewed for security classification. The report, in its entirety, has been determined to be unclassified and contains no information concerning Department of Defense or Atomic Energy Commission programs.

This document has also been reviewed and approved for technical accuracy.

Robert M. Huffaker  
ROBERT M. HUFFAKER  
Technical Advisor

Joseph L. Randall  
JOSEPH L. RANDALL  
Chief, Optical and R. F. Systems Division

F. Brooks Moore  
F. BROOKS MOORE  
Director, Electronics and Control Laboratory